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AMERICAN GEOPHYSICAL UNION

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APRIL 27, 28, 29, 1933
WASHINGTON, D. C.

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INTRODUCTION

The American Geophysical Union is the American National Committee of the International Union of Geodesy and Geophysics, and the Executive Committee of the American Geophysical Union is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now seven sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, and (g) Hydrology. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section; the Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on hydrology.

Annual assemblies of the Union and annual meetings of its sections for the discussion of reports and symposia are held each year. Thus far there have been fourteen such assemblies and meetings, all held in Washington, D. C. The transactions of these annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 66; eighth, 1927, Bulletin No. 61; and ninth, 1929, Bulletin No. 68. Transactions of the tenth and eleventh annual assemblies and meetings held in 1929 and 1930, respectively, were published in one volume in June 1930, those of the twelfth annual meetings were published in June 1931, and those of the thirteenth annual meetings were published in June 1932, in the series of miscellaneous publications of the National Research Council. The present volume, also one of the miscellaneous publications of the Council, includes the transactions of the fourteenth annual assembly. At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The fourteenth annual assembly of the Union and the meetings of its sections April 27, 28, and 29, 1933, were held at Washington, D. C., in the building of the National Academy of Sciences and National Research Council, except for two of the three meetings of the Section of Hydrology which were held in the conference-room of the Geological Survey in the building of the Department of Interior and for one of the three sessions of the joint meeting of the Section of Seismology of the American Geophysical Union and the Eastern Section of the Seismological Society of America which was held at Georgetown University.

The session of the fourteenth general assembly was devoted chiefly to hearing the report of the Committee on Geophysical and Geological Study of Oceanic Basins and to a symposium on relations of hydrology to other branches of geophysics. Progress-reports on geodetic work in the United States and Mexico were presented before the Section of Geodesy, as also papers on gravity-work, on application of radio to astronomical longitude-determinations of the Geodetic Survey of Canada, on the moon's influence on latitude, and on the expansion and developments in the time-service at the United States Naval Observatory. At its meeting the Section of Meteorology had the privilege of hearing a paper by Dr. L. Vegard of Norway on the auroral spectrum in addition to papers by members of the Union and other guests on meteorological problems in relation to radiation, on trade-winds of the eastern Caribbean, on reduction of meteorological data from Cruise VII of the Carnegie, on interesting facts concerning warm and cold waves, on the value of cloud-observations, on the Giko theory explaining the formation of precipitation in relation to fundamental concepts of the polar-front theory, on turbulence-factors of Linke and Ångström, and on the time, type, and areal distribution of tornadoes in the United States. The reports and papers presented before the Section of Terrestrial Magnetism and Electricity included progress-reports on the year's investigations and projects in the United States, Canada, and Mexico, and on the International Polar Year of 1932-33, while the papers related to cosmic rays, to earth-resistivity measurements, to ozone and the sunspot-cycle, to cosmic radio-correlations, and to effect of magnetic activity upon secular change. The meeting of the Section of Oceanography consisted mainly of the progress-reports of eight govern-

mental bureaus and private research organizations engaged in oceanographic work in the United States and Canada; besides these reports, there were papers on investigations of submarine valleys, on monthly sequence of sea-surface temperature on the New York-San Juan steamship route, on air-temperatures and water-temperatures in the West Indian region, on development of our conception of the Gulf Stream system, and on a borehole in the Bahamas. In the Section of Volcanology the papers dealt with volcanic explosions and overthrusts, with the Tertiary Volcano at Cripple Creek, Colorado, and the volcano of Santa Maria in Guatemala, with some features of volcanic sequence in the Cascade Region in Oregon, and with volcanic history of the Magdalena District, New Mexico. The Section of Seismology of the Union held a joint meeting with the Eastern Section of the Seismological Society of America. An interesting series of progress-reports, papers, and informal communications, totaling 39, were presented at the three sessions of this joint meeting covering numerous investigations and developments in seismological research in the United States and Mexico. The Section of Hydrology devoted three sessions to hearing reports of its nine permanent research committees and 25 papers covering numerous investigations and developments in scientific hydrology throughout the United States.

As in previous years, our colleagues in Canada and Mexico took active part in this meeting, submitting progress-reports of governmental activities and of results of geophysical researches stimulated by the national committees. W. E. W. Jackson of the Meteorological Service of Canada was an official delegate in attendance from Canada.

The responsibility of the General Secretary in revising and editing all the manuscripts was lightened through preliminary editing of all manuscripts by the secretaries of the several sections. The cost of publication was borne in part by the allotment by the National Research Council for maintenance of the Union, in part by the annual dues of members of the Union, in part by contributions obtained through the efforts of a special committee of the Section of Hydrology, and in part by the Eastern Section of the Seismological Society of America. The cost was further reduced through the generosity of Messrs. Ennis and Harradon, members of the Union, each of whom read and corrected the final copy before planographing. The preparation of the final manuscript for direct reproduction in this volume was done most efficiently and economically by J. J. Capello as in former years.

Cordial thanks are tendered from the Union's Executive Committee to the speakers, guests, and members of the Union for the cooperation which made possible the success of the fourteenth annual meeting--the proceedings of which give ample evidence of the ever-expanding interest in the scientific as well as the practical aspects of geophysics.

J. A. Fleming,

General Secretary

AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

GENERAL ASSEMBLY

Washington, D. C.
April 28, 1933

REPORTS AND PAPERS

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RESOLUTIONS ADOPTED

(I) RESOLUTION ON THE DEATH OF ROBERT LEE FARIS

(Proposed by the Sections of Geodesy and Terrestrial Magnetism and Electricity)

WHEREAS, By the death of Robert Lee Faris on October 5, 1932, the American Geophysical Union has lost one of its original members and a former Chairman of the Section of Geodesy, and

WHEREAS, Captain Faris was interested in many departments of geophysics and helped to advance scientific knowledge not only by his personal efforts in field and office, but also by the influence he was able to exert through the numerous and important administrative positions held by him, and not least by means of his personal character, which won for him the respect and friendship of those with whom he came in contact, therefore be it

RESOLVED, That the American Geophysical Union, in general meeting assembled, hereby expresses and places on record its sense of loss through his death, and be it further

RESOLVED, That copies of this resolution be sent to Mrs. Faris, to the Director of the U.S. Coast and Geodetic Survey, and to the Chairman of the Mississippi River Commission.

(II) RESOLUTION ON THE DEATH OF JOHN RIPLEY FREEMAN

(Proposed by the Sections of Seismology and Hydrology)

WHEREAS, In the death of John Ripley Freeman the American Geophysical Union has lost a pioneer in the fields of hydrology, geology, and seismology as related to engineering problems, and

WHEREAS, He has rendered notable services to his profession by his generosity in providing traveling scholarships in hydraulics and in financing the translation and publication of foreign books and papers on hydraulics, and by his untiring efforts toward the establishment of a National Hydraulic Laboratory, and

WHEREAS, He through publication and otherwise has greatly stimulated interest in seismology, especially in applications toward saving life and property, therefore be it

RESOLVED, That the American Geophysical Union expresses its sense of great loss in the death of John R. Freeman, not only because of his high engineering and scientific attainments, but also because of his outstanding personal qualities and his earnest and continuous efforts to advance the profession to which his whole life has brought honor, and be it further

RESOLVED, That a copy of this resolution be sent to Dr. Freeman's family.

(III) RESOLUTION ON THE DEATH OF HARLAN WILBUR FISK

(Proposed by the Section of Terrestrial Magnetism and Electricity)

WHEREAS, In the death of Harlan Wilbur Fisk the American Geophysical Union has lost a member long identified with the affairs of the Union and active especially, as both member and officer, in the Section of Terrestrial Magnetism and Electricity, and

WHEREAS, He rendered important service to the advancement of geophysics, particularly through his extensive participation in the magnetic survey of the Earth and through the interpretation of the results thus obtained, therefore be it

RESOLVED, That the American Geophysical Union records this expression of its sense of profound sorrow on the death of Harlan Wilbur Fisk, and be it further

RESOLVED, That a copy of this resolution be sent to Professor Fisk's family, to the President of the Carnegie Institution of Washington, and to the Acting Director of the Department of Terrestrial Magnetism.

(IV) RESOLUTION ON THE DEATH OF LOUIS WINSLOW AUSTIN

(Proposed by the Section of Terrestrial Magnetism and Electricity)

WHEREAS, The death of Louis Winslow Austin has removed from the American Geophysical Union a member always actively interested in the affairs of the Union and one who made notable contribution to geophysics through radio-transmission research and its interpretation in relation to terrestrial magnetism and other geophysical phenomena, therefore be it

RESOLVED, That the American Geophysical Union records this expression of its sense of great loss in the death of Louis Winslow Austin, and be it further

RESOLVED, That a copy of this resolution be sent to Dr. Austin's family, to the Secretary of the Department of Commerce of the United States, and to the Director of the United States Bureau of Standards.

(V) RESOLUTION ON INTERNATIONAL POLAR YEAR

(Proposed by the Section of Terrestrial Magnetism and Electricity)

WHEREAS, The American Geophysical Union regards with satisfaction and approval the progress made in carrying out the International Polar Year program and appreciates the great value of the results that have been and will be obtained during the Polar Year, therefore be it

RESOLVED, That the American Geophysical Union expresses the hope that the International Polar Year Commission will be able to find means for complete analysis, discussion, and distribution of the geophysical data resulting from this magnificent international effort, and that the United States, through its government or otherwise, will be able to assume its proper share in this work, and be it further

RESOLVED, That copies of this resolution be sent to the President of the International Polar Year Commission and to the President of the National Academy of Sciences with the request that the latter make such disposition of this resolution as he may find most effective.

(VI) RESOLUTION ON COSMIC RAYS

(Proposed by the Section of Terrestrial Magnetism and Electricity)

WHEREAS, The importance of studies of cosmic rays is steadily increasing and the need for their continuous registration has been demonstrated, therefore be it

RESOLVED, That the American Geophysical Union recommends that support wherever possible be given to the plan of the Carnegie Institution of Washington and cooperating agencies to establish at certain fixed observatories apparatus and equipment for recording cosmic rays photographically and continuously, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the Carnegie Institution of Washington with the request that he furnish copies to the cooperating agencies.

(VII) RESOLUTION PROPOSING AN INTERNATIONAL COMMISSION ON THE HYDROLOGY OF SNOW AND ICE

(Proposed by the Section of Hydrology)

WHEREAS, The hydrology of snow and ice and the methods of making snow-surveys constitute an important field in the science of hydrology, with a considerable number of research workers in the subject wisely distributed in different parts of the world, and

WHEREAS, There is at present no international commission that covers this field, therefore be it

RESOLVED, That the American Geophysical Union hereby expresses the hope that the International Association of Scientific Hydrology will take appropriate steps at the forthcoming meeting in Lisbon to create a Commission on the Hydrology of Snow and Ice, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the International Association together with copies of the annual reports for 1932 and 1933 of the Committee on Snow of the Section of Hydrology of the American Geophysical Union.

(VIII) RESOLUTION ON APPROPRIATIONS FOR SCIENTIFIC INVESTIGATIONS BY THE FEDERAL GOVERNMENT

(Proposed by the Section of Seismology)

WHEREAS, There are certain types of investigation which can be carried on effectively only by the Federal Government, and

WHEREAS, Large economies accrue to the Government itself from those investigations, and

WHEREAS, Private engineers, geophysicists, and others are almost absolutely dependent on the results of those investigations for the continuance of their own work, therefore be it

RESOLVED, That the American Geophysical Union expresses its hope that the scientific work of the Federal Government will not be too much curtailed under the stress of economic conditions, and be it further

RESOLVED, That a copy of this resolution be sent to the President of the National Academy of Sciences for such use as the Academy may think proper in its capacity as official advisor to the Federal Government.

(IX) RESOLUTION ON NAVAL OBSERVATORY TIME-SIGNALS

(Proposed by the Section of Seismology)

WHEREAS, Accurate time-signals sent out from a strong radio broadcasting station many times daily are necessary for seismological and other geophysical observations, and

WHEREAS, The United States Naval Observatory is now broadcasting such signals seven times daily, therefore be it

RESOLVED, That the American Geophysical Union expresses its appreciation and gratitude for this service, and be it further

RESOLVED, That this resolution be printed in the transactions and that a copy be sent to the Superintendent of the United States Naval Observatory.

R. M. Field, Chairman

D. C. Barton	J. A. Fleming	A. Keith	F. P. Shepard
W. Bowie	N. H. Heck	G. W. Littlehales	T. W. Vaughan
W. H. Bucher	C. A. Heiland	J. B. Macelwane	P. Weaver
E. L. De Golyer	D. W. Johnson	H. A. Marmer	F. E. Wright

The Committee on Geophysical and Geological Study of Oceanic Basins was appointed at the last annual meeting of the American Geophysical Union, April 27 and 28, 1932, for the purpose of promoting, and aiding in every possible way, the study of structural and stratigraphic problems relating to oceanic basins, continental margins, and oceanic islands, especially those forming island-arcs. This Committee is primarily concerned, therefore, with oceanographic problems such as are of paramount interest both to geologists and to those geophysicists whose methods, formulas, apparatus, and techniques are particularly susceptible of adaptation, with or without modification, to an attack upon marine structural and stratigraphic problems. Some of the scientific problems faced by this Committee necessarily border on, or are directly connected with, problems which are of especial interest to the marine biologist and the oceanographer. Thus data concerning the temperature and salinity of sea-water, currents, tides, marine sedimentation, and ecology, together with such phases of oceanography and oceanology as have a bearing on the subject of paleogeography and paleo-oceanology, are also of direct importance to the stratigrapher and structural geologist.

But the formation of the above-named Committee is the outgrowth of the opinion of a number of geophysicists and geologists that there are specific problems connected with the study of oceanic basins and their margins which are primarily geological. It has also been recognized that, in order that these problems may be attacked with the greatest degree of enthusiasm and efficiency, it is necessary to have a closer cooperation between geophysicists and geologists than has heretofore been achieved through previously existing institutional or cooperative agencies, including marine biological laboratories. There are plenty of problems for all, either individuals or institutions; but it has seemed to us that it would be particularly fortunate if we could still further enlist the interest of geologists in the structural problems of oceanic basins and island-arcs by assuring them of the support of the geophysicists.

In his introduction to the "Symposium on the application of geophysics to oceanic basins and their margins" at the last annual meeting, the Chairman of this Committee asked the question: "Are our marine biological laboratories designed to promote the structural studies of ocean-basins? The principal methods of attacking the structural problems associated with oceanic basins and margins are by means of the different branches of geophysics. Geophysics, as its name implies, is concerned with the structure and composition of the geoid. Besides the geophysicists, there are a number of geologists who are adapting geophysical methods to the solution of their problems; and by far the greater number of these appear to be the petroleum geologists, who are naturally, therefore, more closely affiliated with the geophysical and geological fraternity." It is an interesting and highly important fact that, through the powerful urge of economics, the geological and geophysical staffs of a number of oil companies have not only invented and applied geophysical and structural apparatus and techniques which have proved intensely practical as aids in the discovery of oil-pools but, what is still more important to our Committee, have already developed methods and machinery for the exploration of subsurface-structures. Several of these methods, with only slight mechanical changes, may be made particularly effective in procuring much-needed data relative to the structure of oceanic basins and the drowned margins of the continents.

It is not the purpose of this report to attempt to cover all that has been done during the past year, both in this country and abroad, relative to the geological study of oceanic basins and their margins, but rather, having taken into consideration all available information, to state what the Committee has been able to accomplish as to the following:

(I) The promotion of structural studies in oceanic basins during the first year of its organization.
(II) The study of available geophysical methods for work at sea.
(III) Suggestions as to outstanding or fundamental problems which, because of available machinery and techniques, are reasonably certain of solution.

(IV) Suggestions as to available cooperative agencies, both individual and institutional, which are interested in and capable of rendering effective aid.

(I) The promotion of structural studies in oceanic basins

Since the beginning of last May, the following activities have been initiated by your Committee:

(A) A direct gravity- or pendulum-survey of significant portions of Cuba--Sixty-eight stations will have been determined and computed by the terminal date of the Expedition, May 6, 1933. This Expedition was made possible through the cooperation of the Cuban Government, the United States Coast and Geodetic Survey, and the United States Naval Observatory. Following the experience and results obtained from the use of direct gravity in determining subsurface-structures in the Bighorn Basin-Absaroka Region, a net of gravity-stations has been planned for the Cuban terrain, with special reference to information already available as to subsurface-structures, including data derived from a torsion-balance surface. Results already obtained show that the differences in anomalies are sufficiently specific to be of value; and it is expected that, when the anomalies are carefully compared with the other sources of information, it may be possible to discover important structural trends in the Island of Cuba. It is further expected that this information will contribute to our knowledge of the major deformational movements which have taken place in the Gulf and Caribbean Region.

(B) Tables for comparison of geoid with spheroid--At the suggestion of this Committee, and with the help of the Emergency Fund and the cooperation of the United States Coast and Geodetic Survey and of the American Society of Civil Engineers, tables are now being computed for the comparison of the geoid with the spheroid. The tables are highly essential for the ready comparison of gravity at sea with gravity on land.

(C) Preliminary test of seismic methods at sea--Plans have been made for a preliminary test of seismic methods at sea through the cooperation of E. L. De Golyer and the Coast and Geodetic Survey. The technical matters connected with this problem are also being discussed with the officials of the Amarado Corporation, who have achieved remarkable results with this method in mapping detailed subsurface-structures on the continent.

(D) Sonic profiles along transatlantic routes--The question of obtaining sonic profiles along the transatlantic routes is now being discussed with the officials of the White Star Company.

(E) Relative accuracy of sounding-data--A plan is being discussed with Captain Rude whereby it is hoped that the relative accuracy of sounding-data, both as to positions and depths, may be made available for scientific, as well as practical, purposes. A plan is also being discussed by which it is hoped that the Coast and Geodetic Survey may be able to make all of its sounding-data more readily accessible to those interested in submarine topography.

(F) Transfer of Vening Meinesz gravity-machine--Recently your Committee has arranged with the Director of the Oceanographic Institute for the transfer of its Vening Meinesz gravity-machine to the custody of the Hydrographic Office of the United States Navy, where it is understood it will be available for the further determination of gravity at sea whenever occasion warrants, and the necessary submarine may be available.

(G) Tide-gage at Nassau--Your Committee has installed, with the cooperation of the Bahama Government and the Coast and Geodetic Survey, a modern tide-gage at Nassau. This, together with new bench-marks and the promise of keeping continuous and careful records, will eventually supply much-needed information as to the mean tide-level in the Bahama Region.

(II) The study of available geophysical methods for work at sea

After careful study, your Committee has come to the conclusion that the following geophysical techniques, and their adaptation and perfection, are of primary importance:

(A) Sounding--The accurate determination of submarine topography is highly important in helping to determine: (1) The structural problems of the crust beneath the ocean, as well as past changes in sea-level; (2) furnishing essential data for computing gravity at sea; and (3) furnishing data for oceanic circulation and subsurface marine-currents.

The introduction of echo and sonic sounding has been, and will undoubtedly become, an increasing boon to the marine structural geologist. Still further experiments are needed as to relative accuracy in the different types of machines and techniques, but it is unquestionably true that the direct comparison of different machines over the same profile will prove one of the most effective methods. The human factor at present plays an important part in the accuracy of the records. Without entering into a discussion as to the relative merits of the sonic method and so-called "supersonic" method, it may be said that the latter has been proved to be particularly valuable in deep and narrow areas because it tends to eliminate non-vertical echoes.

In connection with projects concerned with sounding-surveys, further attention should be given to the study of sounding-velocities, and particularly to the possibility of adopting regional constant correction-factors for the reduction of echo-soundings. C. C. Ennis, in the compilations of the Carnegie's echo-soundings in the Pacific, has found it possible to develop tables of factors applicable to certain regions by the use of which resulting depths show errors of only about one-tenth per cent as compared with the true depths obtained by more elaborate discussions of sounding-velocities involving temperature- and salinity-measurements.

The recent development of radio acoustic range-finding and the triangulation-methods, as practiced by the United States Coast and Geodetic Survey, are highly essential since, without exact geographical positioning, in most cases, sounding-data are relatively valueless. Every effort should, therefore, be made in future sounding-surveys to locate the positions of the soundings by methods more exact than those usually used in ordinary navigation. In summation, it may be said that "Sounding-surveys are very much needed to provide essential data regarding the detailed surface-configuration of the shelf and its margin, these data being especially needed for the proper solution of problems relating to the nature and extent of past changes of level, and the earlier history of our present shore-lines. In this connection, it should be observed that no satisfactory solution has yet been found for the puzzling phenomena of the submerged canyons or gorges, features which presumably record important events in past continental history" (Johnson).

(B) Time--The accurate measurement of time is essential to the determination of gravity. Without discussing all types of machines now available, or under consideration, for the purpose of measuring gravity, none has as yet been evolved which provides maximum accuracy without the measurement of time. The radio time-signal service of the United States Naval Observatory has played a very important part in measuring the swing of the pendulum, both on land and at sea. The two most important mechanical factors involved in increasing the accuracy of gravity-determinations are, therefore, the perfection of gravity-mechanism and the "clock." To date the only satisfactory machine for measuring gravity at sea is the Vening Meinesz apparatus of the pendulum-type. The relative accuracy of pendulum-determinations may be expressed in the ratio 1:3:7, in which 1 represents the greatest accuracy determined on land, 3 the average accuracy determined on land, and 7 the accuracy determined at sea. The greatest accuracy is obtained by continuous calibration of one or more pendulums with one over a known station. As an illustration of the highest efficiency in the use of a fixed pendulum, one oil company has found it possible to observe groups of stations within an area of one or two thousand square miles, for which the average probable error of the entire group is about 0.15 milligal. Obviously this method could not be applied to the determination of gravity at sea unless a means were devised for a wireless relay from a master-pendulum on a nearby land-station. The other mechanical difficulties of determining gravity at sea would, however, probably more than compensate for the higher degree of accuracy which might be obtained by this method. At the present time, the determination of gravity at sea is absolutely dependent upon radio time-signals for the proper calibration of chronometers. It is hoped that, within a short time, the crystal-clock may be used in the measuring of gravity at sea. Crystal-controlled timekeepers are now being manufactured by the Bell Laboratories and the General Radio Company. The latter company claim an accuracy for their product of one

part in a million, corresponding to about nine-hundredths of a second per day. The Naval Research Laboratory claims much greater accuracy than this. As soon as sufficient crystal-clocks are available, the United States Naval Research Laboratory plans to broadcast time-service on 113 kilocycles every hour of the day, on the hour, except four times when the air is choked with other broadcasts. The increased number of time-signals alone will be a great aid to the determination of gravity on both land and sea, and the installation of crystal-clocks in submarines should simplify the determination of gravity at sea.

(c) Gravity--The Vening Meinesz apparatus is at present the only available machine for the measurement of gravity at sea. To assure success of operation, this machine requires the use of a submarine. While the Committee has given considerable thought and time to the relative accuracy of the different machines and methods for measuring gravity, it is necessary to suggest here only those problems which particularly affect the measurement of gravity at sea. "The investigation of the experimental work on gravity-determinations on the Carnegie during the several months' cruising of that vessel, after the installation of the Vening Meinesz apparatus, indicates that it would be possible to effect improvements which would yield entirely dependable results by the use of this apparatus on board surface-vessels. Despite the short period of the experiments on board the Carnegie, satisfactory determinations were obtained in all the harbors visited, and two successful determinations were made at sea" (Fleming). Vening Meinesz has found that his apparatus is seriously disturbed by the vibration of power-driven vessels, as shown by tests on liners and destroyers.

Aside from the relative accuracy of gravity-determinations on land and at sea, there has been considerable discussion as to the relative accuracy of the torsion-balance and the pendulum on the land. Barton is of the opinion that "Most torsion-balance work, in the case of small intervals between stations, is much more accurate than the pendulum if its error is 0.003. The poorer surveys accumulate a probable error of 0.001 over a distance of 40 to 75 kilometers. Average good surveys will accumulate that probable error over a distance of 120 to 220 kilometers, and the best surveys will not accumulate this error over 120 to 220 kilometers." In answer to this, however, we have definitely proved, last summer, that the anomalies derived from the use of the Brown pendulum-machine in the Bighorn Basin-Absaroka Region were sufficiently accurate to outline the complicated profile of the crystalline basement beneath the thick sedimentary fill. Appended to this report is a study of the anomalies of the Gulf and Gulf Coast region by Donald C. Barton and Maude Hickey, in which they compare torsion-balance- and pendulum-data on land and pendulum-data at sea. This study suggests that a geosyncline exists roughly parallel to the Gulf Coast, the basement underlying both the land and the sea. Helmert (Encyklopädie der mathematischen Wissenschaften, v. VI, 1, B, p. 143) shows that the normal gravity-profile at right-angles to a normal coast is somewhat similar to that found for the Gulf Coast. Entirely aside from the accuracy of the anomalies, serious physical and mathematical problems remain to be solved before the anomalies can be safely used to their full value, regardless of their absolute or relative accuracy. Vening Meinesz' recent work over the Atlantic ridge, as well as the problems raised in Barton's paper, strongly suggest that there may be something wrong in the formulas for topographic compensations.

Thus in relation to Barton's suggestions as to a geosyncline off the Gulf Coast-Louisiana-Texas Region, by analysis of existing gravity-data it is interesting to note that a similar gravity-profile would be found off almost any coast, either off an island such as Cuba, Jamaica, etc., or off a continent. Perhaps nearly all coasts have such a structure as Barton suggests for the Gulf Coast. This is an exceedingly important observation, if true. "The positive anomalies in enclosed basins, such as the Gulf of Mexico, seem, however, to be related to some error of calculation. Until more is known regarding the cause for these anomalies, and until they have been accounted for in the proper formulas, a large error will continue to be introduced, which will materially change the anomalies and thus the implied distribution of masses beneath the gravity-profile." The geoid effect is the same in both Helmert's and Barton's results as it is in the isostatic anomalies. It is quite possible that the positive anomalies, or apparent excess of gravity at sea, will be decreased by the Bowie correction, which may be easily applied as tables for the comparison of the geoid with the spheroid have been completed.

(D) Magnetism--Further investigations of structural relations on islands and oceanic basins and their margins may be expected by utilization of magnetic and electric methods of exploring subsurface-features, for it is a significant fact that many of the isolated islands of the ocean, as well as many shore-lines, are regions of magnetic anomalies. Interestingly enough, this is also the case for gravity-anomalies. We suggest, therefore, that accurate determinations of the magnetic elements be made, whenever possible, where gravity and seismic values have been determined. In addition, these data would supply material for the study of magnetic secular variations and of isoporic lines (lines of equal magnetic change) and of maximum and minimum focuses. Already the study of relative movements of the isoporic focuses and lines on a world basis indicates that they may be concerned with structural changes in the Earth's lithosphere (Fleming).

(E) Seismology--Earthquake studies serve two purposes, namely, (1) to give an index to the forces at work in a given region, including their intensity, and (2) to locate the activity so definitely as to associate it with the formations and structures involved in the movements.

Seismology is particularly important in relation to the structural studies of island-arcs. A discussion of this subject by N. H. Heck is attached to this report (Appendix B). In summation, we may say here that the peculiar significance of the Caribbean Sea, with little activity in its central basin, completely surrounded by regions of earthquake-activity, presents a problem which is duplicated only in the region to the east of a line joining Japan and the Philippine Islands. All available data as to seismic epicenters have been printed, together with the gravity-data, on the chart issued by the United States Navy Hydrographic Office. Owing to the great importance of the study of island-arcs, the Committee strongly recommends that every effort be made to reestablish the stations at Havana (Belen College) and Martinique (Fort-de-France). Stations are badly needed also at Nassau, and one somewhere on the north coast of South America, or an adjacent island, such as Trinidad. With the addition of only these stations, together with the improvement of instruments and regular operations at certain other points, extremely valuable data would be available in a relatively short space of time.

(F) Artificial seismic methods--Too great stress can not be laid upon immediate research as to the application of this method to the study of (1) the thickness of coral reefs on continental margins and oceanic islands, and (2) the study of the drowned continental margins and the floors and substructures of oceanic basins.

Probably no geophysical method, combined with sonic sounding, will, if properly applied, yield such important information. As a single illustration, the sonic profiles of submarine valleys in the Bahama Region, and the submerged continental shelves, do not necessarily represent the true valley-floors which, in many cases, are probably covered to considerable depth by unconsolidated sediment. The artificial seismic method will probably be able to determine the extent and amount of the valley-fills, as well as the thickness of the sedimentary-veneer on the continental shelves. It is the consensus of opinion that "shooting" under water should give even better transmission of energy than shooting in pits under air.

Remarkable results have been obtained, especially by the oil geologists, not only in determining the thickness of relatively unconsolidated surface-sediments on the land, but also in determining subsurface-structures at great distances below the surface. Reflections have been obtained from depths as great as 20,000 feet beneath the surface, and are frequently obtained at depths of from 5,000 to 7,000 feet. As an illustration of detail obtained by this method, one oil company has recently obtained a detailed subsurface-structure on a profile only 900 feet long and at a depth of over 2,000 feet. Without discussing here the relative merits of reflection and refraction shooting, it may be briefly stated, in relation to studies of the thickness of the veneer on continental shelves, that it is best to work from the known to the unknown. Thus continuous profiles should be run extending from the land to the drowned margin of the continent, preferably from some point where the basement-rocks have been reached by drilled wells, so that the average velocity may be computed at the start.

(G) Sea-level--Tide-observations are the only basic datums to which heights on land and depths in the sea can be referred. Fortunately continuous tide-observations

can be obtained at a nominal cost by the use of automatic tide-gages. Thus the principal problem is to find conscientious and regular observers. Since sea-level varies in much the same way over relatively large areas, it is possible to calculate mean sea-level without waiting for the maximum tidal cycle of 19 years in order to be sure that all local fluctuations have been accounted for. Appended to this report is a report (Appendix C) by H. A. Marmer on "The importance of tide-observations" in relation to stability of shore-lines. In summation, we may say that it is highly essential in the geomorphological study of coastal regions that tide-gages be installed, where absent, especially as the fundamental datum-plane of mean tide-level may be computed in a relatively short space of time for the particular region being studied.

(H) Currents and salinities--It should be urged that cooperating oceanographic agencies and institutions give more attention to physical and chemical oceanographic observations useful in the investigation of oceanic currents and circulation, which play so important a part not only in marine biology but also in marine sedimentation (Fleming). As these problems, including salinities, fall so naturally within the fields of investigation of the marine biologist and the oceanographer, it may well fall within his division of labor, rather than that of the marine geologist.

Summary--From the point of view of the geologist, the most immediate problem is the adaptation and perfection of geophysical apparatus and methods to the study of oceanic basins and their margins. In the immediate future, and largely because of the major importance of certain problems, the Committee wishes to emphasize the particular importance of sonic sounding, the determination of gravity at sea or in oceanic areas, and the use of seismic methods in determining both the character and geologic structure of the suboceanic rocks and of those existing beneath the reef-covers of oceanic islands.

(III) Suggestions as to outstanding or fundamental problems reasonably certain of solution

Suggestions as to important problems which, because of available machinery and techniques, are reasonably certain of solution naturally lead to a divergence of opinion which is apt to be colored not only by the personal research interests and geographical position of individuals, but also of institutions. As the fundamental problems facing this Committee are geological and primarily structural, it is only natural and proper that the geophysical investigation of those regions should be suggested which, in the opinion of the geologists, will yield the most important results, not only from the facts to be discovered but also from the point of view of constantly improving the techniques. It would certainly be most unfortunate if, for instance, purely geographic or personal interests were unduly emphasized as to the relative merits of projects in the Pacific and the Atlantic, but the fact remains that geological features of the Atlantic margins are much better known at the present time than the margins of the Pacific. Also fundamental geological problems associated with these margins, such as the nature and origin of geosynclines, special problems in diastrophism (including earthquakes), stratigraphy, and the migration of faunas and floras, have reached the stage where they call particularly for the help of geophysical technique. It should also be noted that the drowned Atlantic margin of the North American Continent covers a much greater area than the Pacific margin. The discovery, if possible, of the relative date or dates of the drowning of the Atlantic margin of the continent, as well as of the thickness of the veneer of unconsolidated sediments, and of the character and structure of the basement-rocks, is of fundamental importance to the discussion of some of the outstanding problems in structural geology, historical geology, and paleo-oceanography, as well as the permanency of ocean-basins.

From the geological point of view, the suggested investigations may be divided into three groups: (1) Investigation of the drowned continental shelves and contiguous islands and coast-lines; (2) the study of oceanic islands, principally in the Pacific, but including Bermuda, especially in relation to the thickness of coral reefs; (3) the study of enclosed oceanic deeps similar to the Gulf of Mexico, especially in the relation of marine to continental gravity-anomalies; (4) the thickness and stability of great delta deposits; and (5) the investigation of structural island-arcs.

After due consideration, the geological members of your Committee also feel that the study of island-arcs is of paramount importance, and that the continued study of the East Indian and West Indian arcs will yield the most immediate and valuable information as to character and origin of major orogenic belts.

Specific regional suggestions are as follows: (1) Sounding-survey of certain significant portions of the continental shelf, especially on the Atlantic Coast between Florida and the Bay of Fundy, a survey which should be so planned as to gain further information regarding the seaward extension of known river-valleys or troughs and to search for others; (2) further sounding-profiles in the Bahamas, the Bartlett Trough, and the assumedly continuous foredeep of the West Indian island-arc; (3) seismic survey of the Atlantic continental shelf to determine, if possible, the thickness of the sedimentary veneer and the lithologic character and composition of the basement-formations; (4) seismic survey of the Bahama Islands to determine, if possible, the relative thickness of the "reefs" and the relatively unconsolidated (and hence lighter) sedimentary rocks; (5) the determination of additional gravity-values at significant positions on the margins of the continental shelf and on the islands in the Gulf and Caribbean Region; (6) the continuation of the determination of gravity at sea around the outer margin of the West Indian arc from Puerto Rico to South America; (7) the reexamination, and possibly the revaluation, of direct gravity-data already available as to the relation of anomalies at sea and on land; (8) the relation of the geomorphology of shore-lines to problems cited above; (9) the relation of the Appalachian geosyncline and other geosynclinal areas to the problems outlined above; (10) the relation of general and specific problems in marine sedimentation, including submarine landslips, to the problems outlined above; (11) the structural and geodetic problems of the Atlantic Ridge; (12) the special and very important problems of seismology and volcanology in relation to the structure of island-arcs, especially in the Gulf and Caribbean Region; and (13) the probable significance of such island-arcs as the East and West Indian in relation to the general problem of ancient geanticlines and major mobile belts. [It is suggested that these arcs have persisted at least throughout the Tertiary and may have afforded paths for the intermittent but recurrent migrations of marine and terrestrial organisms; it is highly suggestive that a combined study of the structure, physical history, and distribution of organisms in relation to island-arcs will yield extremely valuable data concerning fundamental paleogeographic problems.]

(IV) Cooperation of existing agencies

In making these recommendations your Committee fully realizes that it has no funds at its command, nor is it expected necessarily to carry out the plans suggested. Your Committee feels, however, that it may help to promote a number of projects through the coordination of existing agencies as it has done during the past year. Certainly a minimum amount of funds is absolutely essential, but even if a large endowment were available it is fairly obvious that certain necessary machinery could not be bought or operated. An effective program can only be accomplished by the pooling of existing material resources, and enlisting the cooperation of existing personnel and organizations. Further, this method has the distinct advantage over separate or institutional methods in that it forms a wider interchange of ideas and methods, and affords the opportunity for the enlistment of the most highly trained personnel. The existing agencies which, under this plan, can render particular service are:

(1) Certain Governmental bureaus, such as the Naval Observatory, the Hydrographic Office, the Naval Research Laboratory, the Bureau of Standards, and the Coast and Geodetic Survey. The United States Navy and the Federal bureaus mentioned have already rendered indispensable aid to the investigation of oceanic basins and margins, and it is sincerely hoped that their cooperation will be available in the future.

(2) The officers, chief geologists, and geophysicists of the oil companies. A closer association of the "Simon pure" geophysicists and structural geologists with their "petroleum colleagues" will unquestionably lead to the promotion of valuable researches, both on land and at sea. Also the oil companies have valuable geophysical machinery, as well as "trade secrets," which may become increasingly available for purely scientific researches. It should be the function of your Committee to promote such liaison as possible for the benefit of all concerned.

(3) Private individuals who own yachts and are interested in using them for marine expeditions. The larger yachts are essential for extended oceanic work, such as running sonic profiles and collecting bottom-sediments. On the other hand, small boats are essential for work in certain waters.

(4) The use of transatlantic lines in running sonic profiles. The suggestion from your Committee, plus certain cooperation which they might have to offer, should make it possible to enlist one or more of the great steamship companies in this project.

Princeton University,
Princeton, New Jersey

APPENDIX A--THE CONTINENTAL MARGIN AT TEXAS-LOUISIANA GULF COAST

Donald C. Barton and Maude Hickey

An areally extensive gravity-minimum of considerable amplitude lies axially along the Gulf Coast. Three alternative explanations of its cause were suggested by the senior writer a year ago (D. C. Barton, Torsion-balance surveys in Southwest Louisiana and Southeast Texas, Trans. Amer. Geophys. Union, 13th annual meeting, 40-42, 1932):

(A) A geosyncline on the surface of a basement homogeneous in character from the center of the Gulf of Mexico to the center of the continent.
(B) A gulfward regional dip of the surface of the basement in the Gulf Coast area plus a progressive change in the character of the basement from a granitic composition under the continent to a basaltic composition in the center of the Gulf of Mexico.
(C) A geosyncline plus that progressive change in the character of the basement.
(D) A fourth explanation, that it is wholly a salt-effect, was suggested but now seems improbable.

The present report gives the results of some preliminary tentative calculations in regard to those three hypotheses. Hypothesis (C), of the geosyncline plus the change in the character of the basement, gave the closest fit of the calculated to observed profile of Δg, according to our preliminary calculations.

The variation of gravity in southern United States and in the northern half of the Gulf of Mexico is shown in the map of Figure 1. The variation of gravity of the map is based primarily on the pendulum-observations of the United States Coast and Geodetic Survey and of Vening Meinesz' traverse of the Gulf of Mexico in a submarine, but is supplemented by an intimate knowledge of the extensive torsion-balance surveys in Texas and Louisiana. The sea-level value of gravity for each pendulum-station has been corrected to the latitude of Orange, Texas, in order to eliminate the obscuring effect of the latitudinal variation of gravity which has no relation to the structure of the Earth's crust. The latitude of Orange has no special advantage for this problem over any other latitude. The first working edition of this map was made in an effort to extend the gravity-picture of an extensive torsion-balance survey by means of the pendulum-observations; and the only place in which the torsion-balance survey tied into a pendulum-station was at Orange. The values of gravity at the stations in the Gulf of Mexico have been corrected also for the effect of the slope of the continental shelf. The gulfward slope of the contact between the water above and the sediments below is sufficient to produce a considerable gravitational effect which has no relation to the structure of the Earth's crust. The density of the sediments of the continental shelf was assumed to be 1.5. The surface continental shelf was assumed to be composed of a succession of a very few plane surfaces, and each of them was assumed to be infinite in extent. For interpretation in torsion-balance work we have a table which is based on a well-known formula and which gives the gradient for infinite sloping planes with such and such angles of slope and with such and such increase of density of the plane. The gradient which should be produced by the plane slope of each zone of the continental shelf was looked up in the table and multiplied by the width of the zone to give the value of Δg across the zone. The sum of the Δg's for the successive zones from the shore out to the pendulum-station was taken as the

correction. It presumably is approximately correct. The variation of the resulting values of gravity, which are the bases of the isogams of Figure 1, is assumed to be the effect of the structure of the Earth's crust.

To find out which of those three alternative hypotheses is the more probable, we drew up a series of assumed cross-sections of the upper part of the Earth's crust from the Sabine Uplift to the center of the Gulf of Mexico (Figs. 2, 3, and 4). The profile of gravity was calculated for each and compared with the observed gravity-profile.

The following assumptions in regard to the upper part of the Earth's crust were used:

The upper 70 kilometers of the Earth's crust consist (a) of the mantle of sediments; (b) of an underlying granitic basement, with its base at a depth of 10 kilometers; and (c) of a sub-stratum 60 kilometers thick.

Four alternative assumptions were used in regard to the character of the sub-stratum: (a) No change in density--that is, the sub-stratum might be composed of granite or basalt; (b) gradation from a specific gravity of 2.6 at the landward end to a specific gravity of 3.3 at the gulfward end--that is, a gradation from a granitic

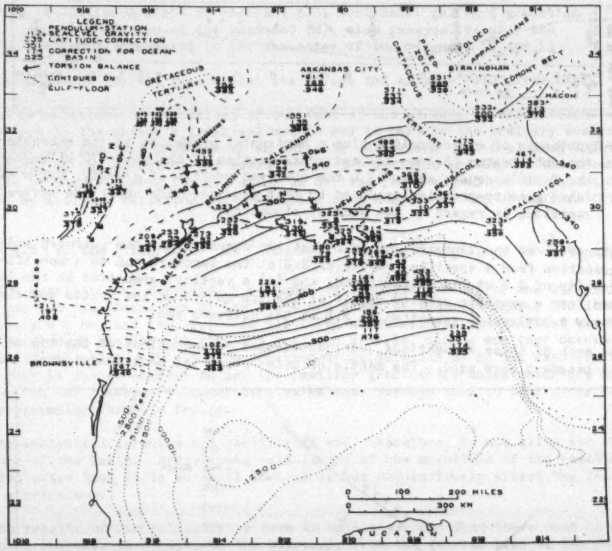

Fig. 1--Map showing the variation of gravity in southern United States and the adjacent part of the Gulf of Mexico [The values of gravity are reduced to sea-level and to the latitude of Orange, Texas. The land pendulum-observations were by the United States Coast and Geodetic Survey. The pendulum-observations in the Gulf of Mexico were by Vening Meinesz. The arrows give qualitatively the general effect shown by the torsion-balance surveys. Of the series of numbers at each pendulum-station, the upper is the sea-level value of gravity, the second is the correction for latitude, the third is the sea-level value of gravity corrected to the latitude of Orange, Texas, the fourth (on the Gulf stations only) is the correction for the slope of the continental shelf, and the fifth is the resulting sea-level value of gravity corrected to the latitude of Orange and as if land extended out across the Gulf of Mexico.]

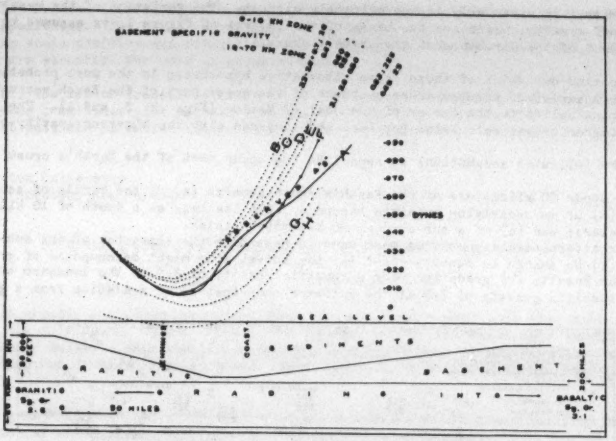

Fig. 2--Hypothesis of a geosyncline plus a horizontal gradation in the character of the sub-stratum [Below--Assumed cross-section of the upper 70 kilometers of the Earth's crust; above--A = the observed profile of gravity, B-H = calculated gravity-profiles produced by that cross-section under the several assumptions in regard to the density-situation]

character at the landward end to a basaltic character at the gulfward end; (c) gradation from a specific gravity of 2.6 at the landward end to a specific gravity of 3.1 at the gulfward end; and (d) a vertical gradation at the landward end from a specific gravity of 2.6 at the top to 3.3 at the bottom and simultaneously a horizontal gradation to 3.3 at the gulfward end.

For each of those assumptions, various assumed conformations of the top of the granitic basement were used. The mantle of water above the continental shelf was not

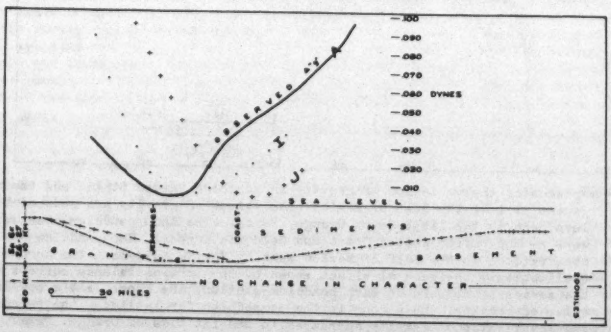

Fig. 3--Hypothesis of a geosyncline plus no horizontal change in the character of the sub-stratum [Below--Assumed cross-section of the upper 70 kilometers of the Earth's crust; above--A = the observed profile of gravity and the calculated profiles of gravity corresponding to the cross-sections below]

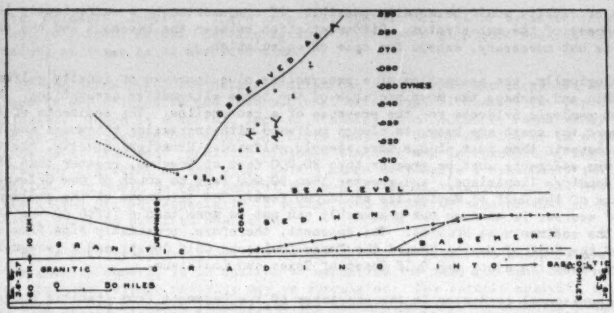

Fig. 4--Gulfward slope of basement plus horizontal gulfward gradation in the character of the basement (M); also geosyncline plus the horizontal gradation in the character of the basement (K and L)

taken into account for the reason that its effect had already been eliminated.

The calculations of the effect of the form of the surface of the basement were made in part by the writer's graphical method and in part by the ordinary analytical formula for the gradient produced by an infinite step-block with a sloping front. The calculations of the effect of the variation of the specific gravity of the basement were made by the following formula which we derived for the gradient which would be produced by a linear variation in the density of a horizontal bed of uniform thickness.

$$U_{xz} = 2Kk \left[z_2[\tan^{-1}(x_2/z_2) - \tan^{-1}(x_1/z_2)] - z_1[\tan^{-1}(x_2/z_1) - \tan^{-1}(x_1/z_1)] \right]$$

where K = gravitational constant; k = change in specific gravity of the bed per horizontal cm; and the dimensions of the block are given by the rectangular coordinates (x_1, x_2), $y = \pm \infty$, and (z_1, z_2). In all these calculations, the gradient was obtained for enough stations to give the gradient profile, and Δg was then obtained by numerical integration. This indirect method of calculation of Δg was used for the reason that it seemed simpler to use the familiar gradient-formulae which are in constant use in our interpretation of torsion-balance surveys than to look up or derive the corresponding formulae for Δg.

The analytical formulae are rectilinear and, therefore, do not allow for the curvature of the Earth. Approximate calculation of the magnitude of the resultant error indicated that it is so small that it should not seriously affect the validity of our conclusions.

The results of our calculations seem to indicate: (A) That there must be a horizontal increase in density of the basement, from the general area of the Sabine Uplift to the center of the Gulf of Mexico; and (B) that a geosyncline must be present in the surface of the basement, with the axes of its trough slightly landward from the position of the present coast-line.

The results of the calculations and the relative fit of the calculated to the observed profile of Δg are shown graphically in Figures 2, 3, and 4. Of the various sets of assumptions which were tried out, the closest fit of calculated to observed profile of Δg was given by the assumption of the geosyncline plus the gulfward increase in density (see Fig. 4).

The gulfward increase of density need not be exactly as postulated in the assumptions. A lesser rate of increase of density would be equally possible if compensated by a sufficiently greater thickness of the sub-stratum, or a greater rate of

increase of density would be equally possible, if compensated by a sufficiently lesser thickness of the sub-stratum. Differentiation between the basement and the substratum is not necessary, except for ease of calculation.

Geologically, the assumption of a geosyncline plus increase of density gulfward is probable and perhaps the most probable of the three alternative assumptions. There is cogent geologic evidence for the presence of a geosyncline. The sediments of the land toward the coast are known to plunge gulfward with increasing thickness and the basement beneath them must plunge more steeply gulfward. Stratigraphically, the thickness of the sediments must be greater than 20,000 feet at Houston, greater than 25,000 feet at Jennings (Louisiana), and greater than 30,000 feet to south of New Orleans. The depths of the Gulf of Mexico lie at 12,000 feet. The thickness of the sediments there, of course, is unknown but presumably can not be more than a fifth of the thickness of the sediments at Houston. The basement, therefore, presumably dips from the center of the Gulf of Mexico toward the Texas-Louisiana Gulf Coast; and a geosyncline, therefore, must lie along the Gulf Coast of Texas and Louisiana.

The horizontal gradation in the character of the basement from granitic under the land to basaltic under the Gulf is in accordance with good geologic theory that the continents tend to be underlain by granitic rocks and the ocean-basins by basaltic rocks.

Petroleum Building,
Houston, Texas

APPENDIX B--SEISMOLOGY AND THE ISLAND-ARCS

N. H. Heck

The relation of seismology to the study of the island-arcs is nowhere better illustrated than in the West Indies Region. The study should include the northern part of South America and part of Mexico. The peculiar significance of the Caribbean Sea with little activity in its central basin completely surrounded by regions of earthquake-activity presents a problem which is duplicated only in the region to the east of a line joining Japan and the Philippine Islands.

The special problems of the region include: The geological significance of the closed loop and especially the geological conditions in Central America and Ecuador and Colombia where the two parts of the loop separate; the significance of earthquake-activity in the Bartlett Deep and also in the Nares Deep; the relation of the seismic activity to the as yet inadequately known submarine contours in the Windward Islands Region and the relation of seismic and volcanic activity in the same region. Others might be added, but these suffice to give the type of problems.

Earthquake-studies serve two purposes: One to give an index to the forces at work in a given region and their intensity, and the other to locate the activity so definitely as to associate it with the geological formations. In connection with the former it must be remembered that geological forces work in geological time. While for isolated portions of the regions we know the earthquake-activity over a period of 400 years, the vital instrumental information scarcely covers a period of more than 30 years, and even now the situation in this respect is not entirely satisfactory. In regard to earthquake-location, a recent study of the Santiago earthquake of February 3, 1932, by Frank Neumann of the Coast and Geodetic Survey has shown that for distances to recording station from earthquakes of less than 2,000 kilometers the velocity of the first preliminary tremors appears to be about 8.0 km per second, which is the same as for the rest of North America for which such studies have been made. Studies in Japan indicate a value of 7.7 or less for that part of the Earth--an essentially different value and sufficient to seriously affect the accuracy if the wrong value were used. This is the sort of thing that needs to be done from the purely seismological viewpoint.

Defects in present instrumental recording have been pointed out. At present the favorable conditions include modern instruments in Puerto Rico (Coast and Geodetic Survey); Panama, Canal Zone; Huancayo, Peru (Carnegie Institution of Washington); and

Bogotá, Colombia (Jesuit). There is a good station with older types of instruments at Port au Prince, Haiti. Certain Mexican instruments give good records but with uncertainty at times as to absolute time.

On the other hand, the Havana station (Belen College) has suspended activity and no reports are printed in the International Seismological Summary for Fort-de-France, Martinique. There is a serious lack of stations which could be remedied by one to the north as at Nassau and one along the north coast of South America or on adjacent islands as at Trinidad. Addition of these stations and improvement of instruments and regular operation at the other points named would give a reasonably satisfactory situation. It would be very helpful to have additional stations in the southern part of the United States, especially if either that at New Orleans or that at Spring Hill, Alabama, could be put into operation.

While gravity-observations and determination of submarine contours are mentioned in the general report, it is desired to emphasize the need for such observations in order that the seismic activity may be correlated. The seismic activity in the region east of the Windward Islands and the nearest part of the Atlantic Ridge should be studied. If there is connection of geological features, there should be such activity. Few authentic earthquakes have been located in this region, but instrumental location has not been satisfactory for the more moderate ones. Seismic activity of the Atlantic Ridge can not be fully studied under present-day conditions, though a station in Bermuda would be very helpful.

U. S. Coast and Geodetic Survey,
Washington, D. C.

APPENDIX C--THE IMPORTANCE OF TIDE-OBSERVATIONS

H. A. Marmer

In connection with the problems coming before the Committee on Geophysical and Geological Study of Oceanic Basins, the systematic and continuous observation of tides at a number of places is of importance in two directions. In the first place, such tide-observations permit the accurate determination of basic datums from which both heights on land and depths in the sea may be measured. And, in the second place, such observations furnish quantitative data for determining coastal stability.

Sea-level is the universal datum to which heights on land and depths in the sea are referred. This universal use of sea-level as a datum-plane is due to a number of advantages it possesses. It is a rational datum-plane and one that everywhere has the same definition; it is, too, a familiar term, and one that is self-explanatory. The geophysicist has adopted the term, and by prefixing the word "mean" has sought to give it a more precise meaning. The expression "mean sea-level" is apparently free from ambiguity and carries an implication that can be determined readily and accurately. However, when it becomes necessary to determine this plane accurately, difficulties appear. For we find that sea-level at any point along the coast varies from day to day, from month to month, and from year to year.

For very rough values the average height of the sea at any place during a day may be taken as approximating mean sea-level. But for any one day sea-level so determined may differ from a precise determination of mean sea-level by several feet. Such values can therefore not be used in precise work. When averaged over a period of a month, sea-level may differ from mean sea-level by as much as half a foot. Even when derived directly from a year of observations the value determined may differ from a precise value by as much as a tenth of a foot. So that where quantitative data are in question a precise determination of mean sea-level must cover observations extending over a period of a number of years.

In tidal work a period of 19 years is considered as constituting a full tidal cycle; for during this period of time the more important of the tidal variations will have gone through complete cycles. It is, therefore, customary to regard results derived from 19 years of tide-observations as constituting mean values. Hence sea-level derived from 19 years of observations is generally considered to constitute a primary determination of mean sea-level and as giving accurately the datum of mean sea-level.

Nineteen years is a very considerable period of time. And if observations covering this period were necessary for an accurate determination of mean sea-level at all points where such a datum is desired, the task would be a very formidable one. Fortunately it is possible to reduce the period of observations by taking advantage of the fact that sea-level varies in much the same way over relatively large areas. It thus becomes possible to make secondary determinations of mean sea-level with considerable accuracy from observations covering a period of a year or even less. The procedure involves the comparison of simultaneous observations at the station for which mean sea-level is desired with observations at some suitable station at which a long series has been obtained.

Thus, with a suitable spacing of a relatively small number of primary tide-stations along the various coasts at which continuous tide-observations are being made, it is possible to secure accurate determinations of mean sea-level for geophysical purposes at many other places by means of short series of observations. It is important, however, that a sufficient number of tide-stations be in continuous operation for this purpose.

In connection with the question of coastal stability, the tide-observations furnish the data by means of which the emergence or subsidence of a coast may be determined quantitatively. There is indubitable evidence that in past times land and sea have changed in relative elevations. Are such changes taking place now and, if so, at what rate? It is to these questions that tide-observations will furnish the answer.

It is to be noted in this connection, however, that the variations in sea-level from year to year are generally of much greater magnitude than the changes in relative elevation of land to sea during several years. It follows, therefore, that only by continuous observations covering a number of years can such relative changes in elevation be determined. But in this case, too, in connection with the relatively small number of primary tide-stations in continuous operation, short-period observations may be used to determine coastal stability at any desired place. For example, if at a given place it is desired to determine whether or not emergence or subsidence is taking place, a year of observations may be made and mean sea-level determined by comparison with some suitable nearby tide-station. A number of years later another year of observations may be taken at that place and again reduced to a mean sea-level value by comparison with a primary tide-station. The difference of the two mean sea-level values at the given place will then be a measure of the change in the relative elevation of land to sea at that place.

Another interesting question, upon which continuous tide-observations may throw light, is that with regard to stresses within the Earth. In a recent study of the yearly values of sea-level, Professor William Fitch Cheney, Jr., found evidence that makes it appear that possibly the Atlantic coast of the United States is at the present time suffering changes of a differential character, the northern portion appearing to be rising, the central portion appearing to be subsiding, and the southern portion appearing to be rising. If such differential changes are actually taking place, they unquestionably give rise to differential stresses of geophysical importance. The tidal data at hand at the present time are altogether insufficient to prove such changes conclusively; but it is of interest to note that the sea-level values derived from tide-observations will furnish the data that throw light on this question.

The above is but a brief outline of the problems involved in the determination of mean sea-level and in the determination of coastal stability. What is intended, primarily, is to direct attention to the importance of continuous tide-observations in connection with the work of the Committee on Geophysical and Geological Study of Oceanic Basins. Fortunately such observations can be obtained at merely nominal cost by the use of automatic tide-gages.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SYMPOSIUM ON RELATIONS OF HYDROLOGY TO OTHER BRANCHES OF GEOPHYSICS

THE RELATION OF HYDROLOGY TO THE BOTANICAL SCIENCES

Robert E. Horton

Hydrology has a more or less intimate relation to all the geophysical sciences. There are other sciences which are terrestrial, although not counted as geophysical, where the interrelations with hydrology are especially marked. I refer in particular to the biological sciences. Direct interrelations of animal life to hydrology are not wanting. Examples are furnished by the relation of the migration of fishes to fresh-water floods of streams and by the life-habits of many oysters, which seek the transition-zone between salt and fresh water for elements vital to their existence and for protection from their enemies, and suffer if the ordinary course of the hydrological cycle is disturbed. Darwin directed attention to the agronomic importance of earthworms, but it remained for Lawes, Gilbert, and Warington (The amount and composition of drainage-waters collected at Rothamsted, J. R. Agr. Soc. Eng., v. 27, 275, 1881) fifty years ago to point out that in some of the best agricultural soils earthworm perforations apparently provide the principal means of entrance of rain-water to and escape of air from the soil, thus permitting the underground phase of the hydrological cycle to be enacted and moisture-supply for vegetation provided.

It is the interrelations between hydrology and certain of the botanical sciences, particularly plant ecology, to which attention will be particularly directed.

A plant which has its root-system in the soil leads a sort of double life. Its aerial portion is in an environment of air, light, sunshine, and radiation. Its root-system lives in an environment of soil, soil-solution, and soil-air. If the conditions in the two environments are harmonious, the plant thrives. If the environment of one part of this Siamese duality is unfavorable, both parts suffer. Thus the plant may die of frost in its aerial or drought in its underground environment when conditions in the other environment are favorable to life and growth.

As regards the water-relations of plants, the reciprocal arrangement is still more marked. The root-environment derives its moisture-supply from the atmospheric environment, while the aerial plant derives its water-supply from the soil-environment.

Plant ecology and hydrology are so interwoven that it is impossible to fully describe their relationships without writing a treatise on one or the other subject.

The science of hydrology centers around the phenomena of the hydrologic cycle--rainfall, runoff, evaporation. The most familiar example of the stage-setting in which this cycle is enacted is, of course, the drainage-basin of a stream. But a plant, with its bit of soil-environment and its bit of aerial environment, forms all the stage-setting necessary for the enactment of the hydrologic cycle. The transpiring stream takes the place of the Nile or the Amazon in the drainage-basin by transporting the water from the collector to the evaporator. This is illustrated by the familiar experiment of growing a plant in a closed space. The ecological classes of plants are based on their hydrological preference of environment--hydrophytes, hygrophytes, mesophytes, and xerophytes.

There is a fact of sufficiently widespread application that it might even be called a law of interrelation between the hydrology and natural vegetation of a region. The natural vegetation of a region tends to develop to a point where it can utilise all of the infiltrated rainfall. The word "tends" is used above in expressing this relationship because evaporation from the soil always takes its toll and because fulfillment of the law may be inhibited by other factors. Much the same idea, stated in converse form, is known in France as the "law of Dausse." Dausse found that there was no accretion to the water-table as long as water-losses exceeded the rainfall.

The process by which soil-moisture is conserved for plant-use has only recently been clearly recognized (Veihmeyer and Hendrickson, Soil-moisture conditions in relation to plant-growth, Plant Physiology, v. 11, No. 1, 71-82). Owing apparently to the fact that soil structure is cellular or vesicular as well as capillary, the soil can

hold a certain quantity of moisture in equilibrium against gravity at all heights above the water-table. This quantity is designated the "field-moisture capacity." Water used by plants lies in the zone between the wilting point and the field-moisture capacity. If there is a deficiency in field-moisture, all infiltration goes to replenish this deficiency until the field-moisture capacity is restored. Thereafter the excess percolates downward to the water-table. Thus all the water which can be utilized by vegetation is retained in the soil and only the excess is rejected.

Excepting for loss by evaporation from the soil, the law stated is apparently nearly fulfilled in many arid and semi-arid regions, where little infiltration is allowed to escape downward to the water-table (Rainfall interception and consumptive use of water in the Santa Anna River Valley and Coastal plain, Bul. 33, Dep. Public Works, Water Resources Div., Sacramento, Calif., 1930). In humid regions the law is generally fulfilled during the growing season. In regions of dry agriculture its fulfillment is approximated, since grain crops utilize not only all or nearly all the summer infiltration but the equivalent of several inches' depth of infiltration from winter precipitation stored in the soil.

Rainfall minus runoff equals the water-losses for any area. The water-losses are of three kinds: (1) Interception of rainfall by vegetation; (2) transpiration by vegetation; and (3) evaporation from the soil.

It happens that the stomatal cavities within which transpiration takes place are necessary to the absorption of CO_2 and the escape of oxygen. Botanists are not fully agreed as to the extent to which the escape of water-vapor from the stomata by transpiration is a necessary physiologic function and the extent to which it is an unavoidable waste. The transpiration-stream maintains turgor in the succulent tissues of the plant and supplies them with needed minerals from the soil. Since there is a close correlation between transpiration and growth, transpiration may be considered hydrologically as a necessary and beneficial use. Interception is a loss incidental to plant-growth, though generally detrimental by reducing the ground rainfall. Evaporation from the soil is unavoidably concomitant to growth, since it is derived from soil-moisture, like transpiration, and is closely correlated with transpiration. While, of course, water losses occur by evaporation alone from bare areas, it is fair to say that on a vegetated area all the kinds of water-losses are either necessary, incident to, or unavoidably concomitant with the growth of vegetation.

The determination and separation of these items of water-losses are matters in which the hydrologist, ecologist, and agronomist are all vitally interested.

To those whose interest lies primarily in hydrology rather than in botany, it is pleasing to note that a vast amount of work of first-order importance to scientific hydrology has been carried out by biolegical investigators. To Poiseuille, the physiologist, we owe the law of capillary flow. For quantitative knowledge of transpiration, the most important of the hydrologist's triumvirate of water-losses, we are indebted solely to botanical and agronomic investigators from Hellriegel, Wollny, and other pioneers down to Briggs and Shantz and others still working in this important field.

Determination of the transpiration by trees, particularly mature trees, is a difficult matter, on which, with the exception of the work of Höhnel (Robert E. Horton, Transpiration by forest trees, Mon. Weath. Rev., v. 51, 571-581, 1923, contains a translation of Höhnel's data), little has been accomplished. The leaf crop of a forest is not harvested and cannot be used as a basis of estimating water-requirements, as is done in the case of agricultural crops. Better knowledge of water-losses from forests, particularly natural stands of trees in forest-covered areas, is greatly to be desired. In closing I wish to suggest a method by which this result may be accomplished.

The extensive system of stream-gagings maintained in the United States by the United States Geological Survey and other agencies furnish a basis for determining the total water-losses and hence approximating the vegetational use of water over a large portion of the area of the United States. Heretofore, owing to inability to make needed corrections for gain or loss of soil-moisture and ground-water storage, it has been possible to determine the water-losses only for average conditions or relatively

long periods. Following the pioneer work of W. S. Auchincloss at Bryn Mawr, Pennsylvania (Waters within the Earth and the laws of rainflow, Philadelphia, 1897), and two British hydrologists, Samuel Hall (Stream-flow and percolation-water, Trans. Inst. Water Eng., London, v. 23, 92-127, 1918) and D. Halton Thomson (Hydrological conditions in the chalk at Compton, West Sussex, Trans. Inst. Water Eng., London, v. 26, 228-261, 1921), a method has recently been developed by the author whereby it is possible to determine with considerable accuracy from rainfall and runoff not only the underground water-losses but the accretion to and draft from the soil-moisture zone for any chosen time-interval. Thus, for example, if a forest area of a given type covers an entire drainage-basin, the runoff from which has been gaged, it is possible to follow the march of transpiration from this forest somewhat closely. The method can only be applied to areas underlain by a perennial water-table. Given such an area, it requires only the existence of good daily records of rainfall and runoff, although its accuracy and the facility of its application are increased if ground-water-level records are also available.

The labor involved in its application is small compared with the tedious process of soil-moisture determinations from field-samples, now sometimes used for determining the amount of water consumed by growing vegetation.

This method is cited as affording an instance where hydrologic data collected primarily for other purposes may be of direct use in connection with various sciences comprised under the general heading of "botanical science."

Voorheesville, New York

RELATION OF METEOROLOGY TO HYDROLOGY

N. C. Grover

As the sections of Hydrology and Meteorology in the Geophysical Union are organized and the respective fields of activity are defined, the interrelation of interests of the two sections is so obvious as to appear to render discussion unnecessary. Their fields added to that of oceanography cover that never-ending cycle of motion of water wherein it condenses in clouds, is precipitated as rain or snow, flows over and through the Earth's crust, accumulates largely in oceans, is taken into the air again by evaporation and transpiration, and is again condensed into clouds and precipitated. The Section of Hydrology works within that portion of this cycle that is represented approximately by the passage of water over and through the Earth's crust, the Section of Meteorology works within that portion represented approximately by the passage of water through the atmosphere, and the Section of Oceanography works within that portion represented by the oceans. Each field of activity begins, therefore, where another ends, and the work of one section is related to and must be consistent with the work of each of the others. The obvious points of contact between the sections of Hydrology and Meteorology are in those phases that relate to the transfer of water from the atmosphere to the Earth's crust (precipitation) and to the reverse action of transfer from the Earth's crust to the atmosphere (evaporation).

The statistical records and the results of scientific researches in both hydrology and meteorology are of great interest and value to man because of the information afforded thereby as to the supplies of water, both on the surface and underground, that are or may be made available. The data are also used in scientific studies regarding the effects of water on the structure of the Earth's crust and other problems in geomorphology. Such information derived within the fields of activity of both sections is essential to safe developments of agriculture by irrigation, municipal water-supplies, industries needing large quantities of water for process uses, power-plants, both hydraulic and steam, and for planning bridge and culvert openings, elevations of surfaces of highways, and many other uses related to the work and play of man. For many of these purposes, water is the limiting factor. It limits the area that may be irrigated, the size of power and industrial plants, and the size of cities. The information is used by engineers as a basis for design, by financiers as a basis for investment, by attorneys and courts as a basis for adjudication, and by State officials as a basis for administration. Information with respect to water has therefore much more than abstract scientific value. Reliable information with respect to it is always sought because of its practical and continuing relations to man's activities along many lines.

Because of the importance of water with respect to human activities, there is a great interest with respect to annual and cyclic variations in precipitation which are, of course, reflected in comparable variations in both surface- and ground-waters. Both sections (Hydrology and Meteorology) are interested in the remote causes that control weather and its variations, in the reasons for periods of floods and droughts and for the cyclic character of climatic phenomena, if for no other reason, to serve as a basis for reliable long-time predictions of major climatic variations.

Because of the many and varied uses of water and the importance of reliable information with respect to its occurrence, the relationships of precipitation to runoff, of temperature to runoff, and of temperature, wind-movement and relative humidity to evaporation are always being investigated. Of these, the relation of precipitation to runoff appears to be the simplest and is the one most commonly used. Attempts have been made to express this relation in various ways, some using the form of a ratio of runoff to precipitation as a fixed or variable percentage-relation, others express the relation as a difference or residue. Unfortunately, from my point of view, the percentage-relationship has been most generally adopted. The concept of runoff as a residue of precipitation that is left after evaporation and transpiration have taken their tolls is apparently not generally understood. In considering this concept, sight must not be lost of that portion of the precipitation that is discharged into an ocean through underground channels and so does not appear as measured runoff. Generally the amount of such underground discharge is so small in comparison with the surface runoff as to be negligible, but in some regions, notably those having lava or cavernous limestone strata, the underground discharge may be large and in those instances must enter into any comparison of runoff with precipitation.

As a result of the failure to consider runoff as a residue of precipitation, ludicrous if not serious errors are made. I will refer to only two instances that have come to my immediate attention. A prominent engineer whose previous experience with water had been intensive but local reported on the supply of water for an irrigation-project in New Mexico to be derived from a river draining a basin on which the mean annual rainfall ranged from 10 inches in the lower altitudes to 25 inches in the higher altitudes. He estimated that the supply of water available for irrigation would be 50 per cent of the total rainfall on the basin because that relation happened to be about the proportion of the rainfall that appeared as runoff in the region having about 40 inches of rainfall where he had previously worked. If he had experienced the concept of runoff as the residue of precipitation, he would have estimated less than an inch in depth of runoff instead of the equivalent of 8 to 10 inches in depth on the basin. As a result his report was grossly in error in its fundamental findings.

In another region an engineer had occasion to compare runoff records from two near-by rivers in the basins of which the annual rainfalls were 40 inches and 30 inches, respectively. He reached the tentative opinion that something was wrong with the records of rainfall or runoff or both because the records for the latter basin showed a runoff of about 30 per cent of the precipitation while those for the former showed nearly 50 per cent. A study of the data on the basis that runoff is a residue from precipitation cleared up his doubts because all records then appeared to be consistent.

Of course, the annual totals of evaporation and transpiration from a basin are not uniform. They vary with many causes, but when averaged for entire basins the range of variation is generally between 18 inches in depth for northern parts of the United States and about 25 inches for southern parts. These figures are true only for those regions in which there is sufficient rainfall to yield such quantities of water. The difference between the depth of water carried into the atmosphere by evaporation and transpiration and the precipitation in inches of depth will be the runoff within reasonable limits of error.

Although precipitation varies both regionally and locally, and an accurate determination of the average precipitation on even a small drainage-basin is impossible, and although there are many difficulties in measuring the precipitation at any point due largely to the effects of air-currents, the transfer of water from the atmosphere to the Earth must be considered as directly measurable, at least approximately. In spite of the difficulties involved and of the recognized inaccuracies in individual records and in averages for drainage-basins and regions, the records of precipitation in this country, many of which extend over more than half a century, are of inestimable value and are widely used as the bases for estimates of availability of water-supplies.

The water transferred from Earth to atmosphere cannot be measured directly. The change is invisible, is taking place practically continuously and under widely varying conditions ranging from direct evaporation from free water-surfaces to the transpiration from the tiniest of growing plants. The approximate results of these processes are determined indirectly as differences between the amounts of water supplied and the amounts remaining under the conditions that may be studied. I have already referred to the gross annual amount lost to the atmosphere from a drainage-basin in a humid region in indicating a proper approach to the relation of precipitation to runoff.

By a converse approach, the difference between the measured precipitation and the measured runoff plus groundwater-flow appears as the total transfer of water to the atmosphere from the drainage-basin under consideration. This total is made up, however, of many parts varying with many factors related to atmospheric conditions, water exposure, nature of vegetation, and season in its relation to rates of plant growth. Within this range of factors are many problems for study. From past and future studies within this field of relationship of hydrology to meteorology, many facts have been or will be discovered which will serve man in problems touching upon the necessities of agriculture, industry, commerce, and life itself.

U. S. Geological Survey,
Washington, D. C.

DISTRIBUTION OF PRECIPITATION IN THE CUMBERLAND AND TENNESSEE BASINS

Montrose W. Hayes

This paper is a very brief summary of a special bulletin on the climate of the Cumberland and Tennessee basins, now being published by the Weather Bureau.

The Cumberland and Tennessee basins lie between longitudes 81° 30' and 88° 30'. In a general way they form a rough quadrilateral, with its greatest length about 400 miles from east to west. Also, they may be likened to concentric arcs, the Tennessee being the outer and southerly one, with a total area of 40,667 square miles. The Cumberland is much smaller; its total area is 17,880 square miles. Combined they are 29 per cent of the area of the entire Ohio Basin.

The eastern part of the Tennessee Basin embraces the western slope of the mountainous country of North Carolina and southwestern Virginia, and all of the Tennessee portion of the Appalachian Plateau. The Cumberland Basin does not stretch as far to the eastward; it heads in the Cumberland Plateau. The steep slopes in the eastern parts give way to very gentle slopes in the country to the west of the Appalachian Plateau. However, the difference in elevation between the eastern and western borders of the Tennessee Basin is pronounced, the extreme fall being somewhat more than 6,000 feet. This difference in elevation causes a marked difference in the precipitation. Then, as the eastern precipitation is caused by storm types that are entirely different from those that give the western rains, there is, necessarily, a large variation both as to amount and, more important, seasonal occurrence.

It may be said in a general way that the annual amount of precipitation decreases rapidly as we progress in a westerly direction from the crest of the Blue Ridge to the Appalachian Plateau, then very gradually to the western border of the basins. There is, however, one marked exception to this statement. The precipitation over that portion of the Appalachian Plateau lying to the north of the French Broad River is just about equal to that occurring over the extreme western part of the area.

The greatest rainfall over the country west of the Appalachian Plateau comes in the winter and spring, and is caused by barometric depressions from the west or southwest. In the mountain country, especially that portion south of latitude 36°, the greatest amounts are in the summer. The latter region from time to time is visited by storms of tropical origin, and phenomenally heavy rains fall. This fact has some weight in raising the annual normal of the extreme southeast part of the Tennessee Basin.

It is interesting to note that the area having the heaviest precipitation is along the Blue Ridge between Georgia and extreme southwestern North Carolina, where

the direction of the mountain range is almost west to east, but bending slightly to the northeast. The annual amounts at some of the high places of observation are more than 80 inches.

Where the Blue Ridge stretches in an almost north and south direction the amounts are lighter, except here and there in the most elevated region of the entire basin where locally large amounts are undoubtedly due to topography. Then, progressing northward into the western tip of Virginia the annual fall is less than it is in the northwestern part of the basin, which may be said to lie in the Mississippi Valley Region.

Floods in all parts of the Cumberland Basin, except perhaps in very small streams, occur in the winter and spring, as the basin does not extend into the high, mountainous country of the east, where heavy summer rains are the rule.

In the Tennessee Basin, having a much larger area than the Cumberland, and a much greater east and west extent, conditions are quite different. Floods in the mountain streams occur with the greatest frequency in the summer, and flow into a main stream, or the Tennessee below the confluence of the Holston and the French Broad, which is comparatively low. Then, in the winter and spring, when flood-producing rains are falling over the comparatively low country west of the Appalachian Plateau, there is, as a rule, little, if any, flood-water coming out of the mountain streams. This is a fortunate condition, not only for the lower Tennessee Basin, but also for the lower Ohio and the lower Mississippi rivers, for were the flood-producing rains to come in the same season in both the eastern and western parts of the Tennessee the results would be evident as far south as the Gulf of Mexico.

Snow in the Cumberland and Tennessee basins is heavy at times, but it does not remain on the ground long, except in the very high regions, and no extended discussion of it would be necessary in a paper on precipitation. In fact, for practical purposes, all the precipitation might be considered rain.

U. S. Weather Bureau,
Washington, D. C.

GLACIERS AND GEOPHYSICS

Harry Fielding Reid

To consider the relation of glaciation to other branches of geophysics we must first develop the cause of glaciation; and this will require us to recall some ideas which, though elementary, are fundamental, and it is by keeping fundamental principles in mind that we can build most securely the superstructure.

The first requisite for glaciation is the excess of the annual snowfall in a more or less limited region over the melting and dissipation. A mass of snow is thus accumulated which grows in thickness, is gradually converted into ice, and slowly flows away into a region where not only is the annual snowfall all melted but also the ice which has flowed into it.

Whether the glaciation shall increase or decrease depends not on the annual snowfall, nor on the annual melting, but on the difference of these two factors; and small variations in either one may result in a fairly large percentage-increase in their difference. This is one source of difficulty in tracing some variations of glaciers to their causes. In the arctic and antarctic, for instance, the snowfall is far smaller than in many regions of the temperate zone where the annual snowfall totally disappears in the spring, but the loss there is also smaller, and, in general, we can only form an idea of the difference by the result and not vice versa.

We take a second step. A glacier is divided into two parts by the névé line, the accumulator and the dissipator. In the first there is annual accumulation and in the second annual dissipation. If the glacier is in equilibrium, that is, neither increasing nor decreasing, the two must be equal and equal to the flow of the ice through the névé line. This can be expressed in two simple equations thus

$$Aa = F = Dd$$

where A and D are the areas of the accumulator and dissipator, respectively, a is the average annual accumulation per unit-area of the accumulator, d is the average annual loss per unit-area of the dissipator, and F is the total annual flow through a section at the névé line. This equation enables us to find a relation between the areas of the accumulator and the dissipator in terms of the average accumulation in the former and dissipation in the latter. Although this varies in different glaciers, its average value for the glaciers of the Alps is about 3 to 1. When we try to imagine the appearance of the ice-sheets of the Glacial Period, we must picture to ourselves a great mound covered by snow surrounded by ice from all the snow, and much ice melts in the summer; and the snow-covered accumulator must have had an area several times as large as the snow-free dissipator. It has been suggested that the cyclones followed a path across the continent near the edge of the ice-sheet, and by heavy precipitation of snow caused a great extension of the ice. But if there had been any accumulation in this region it would have become a center of dispersion, and the ice not only would have extended much farther south but its direction of flow would have been very different from what it was.

Let us glance at the great variations that have taken place:

(1) The five great advances of the Pleistocene with the intervening interglacial periods.

(2) Historic variations. Our knowledge of these does not reach far into the past. We know that in the north of Europe and of the Atlantic the glaciers were much less extensive in the early part of the eighteenth century than they are now, and that a great advance took place towards the end of that century, followed by a retreat which still continues. Have similar changes taken place in Alaska? Vancouver found Glacier Bay full of ice in the 1790's, and the glaciers there have been in marked retreat ever since. Moreover, there is evidence enough that the great advance in Vancouver's time was of comparatively short duration, and that before the advance the glaciers were smaller than they are now. In the antarctic the Ross Barrier is 17 to 20 miles behind its position when Ross discovered it in 1843; and many of the glaciers show clearly that they are considerably smaller now than they were not long ago. There is a strong suggestion that these changes were world-wide, but the correlation is not close.

(3) Brückner has shown that the glaciers of the Alps undergo fluctuations in their length with varying intervals, but averaging roughly about three times per century. (The last two groups are the variations which our Committee on Glaciers is especially concerned in recording.)

(4) Seasonal advances and retreats. During the winter the flow of the ice continues, but the covering of snow prevents any melting and consequently the end of the glacier advances; when, in the spring, the snow melts off the end, the ice melts more rapidly than it advances and there is a retreat. These variations have been measured on one of the Grindelwald glaciers by Baltzer over a period of four years and showed a variation of about 20 meters. But these are of little consequence.

(5) Adventitious variations. In 1899 there were some very severe earthquakes in Yakutat Bay, Alaska. Immense quantities of snow and ice were shaken off the flanks of the neighboring mountains upon the glaciers below. A few years later Tarr and Martin spent several seasons in this region and they found that the glaciers made extraordinary advances both in extension and in speed. But the advances did not occur at the same time. Some glaciers were two or three years later than others in their advance. The advance was due to the sudden great addition to the accumulators which increased the rate of flow and upset the approximate condition of equilibrium of the glaciers. But it took different times for this abnormal flow to reach the ends and carry forward the ice, on account of the different lengths of the glaciers and probably also on account of topographic differences. We should expect that it would take years to restore the normal amount of snow to the flanks of the mountains, and that avalanches would be less frequent. The accumulators would therefore receive less than the normal supply and the glaciers would, for a time, become smaller than they were before the earthquakes. Some years ago a great landslide from the south side of Mont Blanc fell on the Brenva Glacier. The great weight of the slide and the protection it afforded against melting produced, a year or two later, a marked advance of the glacier. Such adventitious changes should be carefully distinguished from the historic and Brückner variations mentioned above.

It is evident that the more important variations of glaciers are to be explained by variations of climate; to explain them we must call upon the meteorologists to become glaciologists, or the glaciologists to become climatologists. There is a reflex action that is important; a large glaciated area reduces the general temperature of the region and thus tends to increase the accumulation and the extent of the area. If, for any reason, the accumulation diminishes, the extent of the glaciation will become smaller, the general temperature of the region will rise, and the retreat will be hastened. This is probably an important cause of the enormous changes in the extent of the ice during the glacial and interglacial periods of the Pleistocene.

It is interesting to consider the way in which glaciers vary. Let us suppose that there is a fluctuating supply to the accumulator. As the supply increases the accumulator thickens and the flow through the névé line increases, but with a marked lag behind the supply. A quasi-wave moves down the glacier with a greater speed than that of the ice and later carries forward the end of the glacier rather quickly. Then the speed slackens and the glacier slowly melts back. The variations in the accumulators of several glaciers may be synchronous but the times of advance may be quite different, depending on the lengths of the glaciers, the slopes, and probably on other conditions. This often makes it difficult to fix the date of a general advance within several years.

The relation of glaciers to hydrology is evident. To the hydrologist the glacier is a great reservoir which conserves the annual precipitation and yields it up, principally during the summer, when it can be used for irrigation. As many of the existing glaciers are situated at a considerable elevation, they develop important water-power. Advantage is taken of these conditions in the mountainous countries of Europe; and they are coming into use in our own country.

There seems to be no relation between glaciology and oceanography unless we go back to the Ice Age. It is clear that the level of the ocean must have been lowered when large amounts of water were locked up in the ice-sheets, and raised when these sheets disappeared. These changes are attracting more attention from geologists now than they formerly did.

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SOME RELATIONS BETWEEN GROUND-WATER HYDROLOGY AND OCEANOGRAPHY

David G. Thompson

In many areas along the sea-coasts of the world the water-supply for human use is derived largely, and in some areas wholly, from underground sources. Because of the proximity to the ocean in these areas, in some respects the geologic and hydrologic conditions that govern the occurrence and movement of ground-water are quite different from those in inland areas, and to properly interpret them the ground-water hydrologist must avail himself of facts developed by the oceanographer.

These conditions are encountered in a marginal zone that in different localities may extend only a few feet or many miles inland from the coast, and presumably for greater or less distances out beneath the ocean. These special conditions have been recognized and extensively studied for many years, for example, in the lowland-area of Holland that lies between the Zuider Zee and the North Sea, and on Long Island, New York. Within recent years more or less attention has been given to these conditions in many of the coastal states of the United States, and in the Hawaiian Islands and Cuba. It is the purpose of this statement to indicate some of the problems of ground-water hydrology that are related to oceanography.

The ground-water hydrologist is interested in three important and well-recognized characteristics of the oceans.

First, the water of the oceans is distinctly salty and is unfit for practically every economic purpose for which the fresh ground-water of the land is developed; and because of its salinity, the water of the oceans has a greater density than the fresh ground-water with which in some places it is in contact.

Second, the water of the oceans is subject to widespread fluctuations of its surface-level, which we call the tides and these may produce fluctuations of the water-level or artesian pressure in water-bearing formations in the landward portion of the coastal area.

Finally, the oceanic basins are and have been the scene of widespread deposition of sediments that form water-bearing formations or aquifers, as well as more impervious formations which may prevent free movement of water from one aquifer to another.

The interest of the ground-water hydrologist in these conditions, of course, is a practical one in so far as it bears on his studies to determine the extent to which supplies of potable water can be obtained from underground sources. Nevertheless, his observations in the coastal areas are of scientific interest in that they yield information in regard to certain conditions and phenomena concerning which little is known.

One of the principal problems to be considered in coastal areas is the possibility of contamination of the fresh water-bearing horizons by salt water moving in from the oceans. In many coastal areas it is difficult to obtain fresh water, or the fresh water is replaced by salt water upon the withdrawal of comparatively small quantities of water. There is considerable variation in conditions from place to place. For example, in an area in Brooklyn, on Long Island, the water has a chloride-content ranging from a few hundred to as much as 8,800 parts per million, but not many miles away at Coney Island and on the barrier beach known as Long Beach--where a source of salt water is much nearer at hand--the chloride-content of water from deep wells is less than 10 parts per million. On the other hand, in North Carolina in certain localities 25 to 50 miles inland from the coast all water encountered in deep wells has been too salty to use. On the east coast of Florida fresh-water springs are reliably reported to arise from the ocean-bottom several miles offshore and wells near the shore in some localities yield water with a chloride-content of only a few parts per million; but in contrast, over large areas elsewhere on the peninsula, some of them many miles inland, the water is too salty for domestic use. One of the most important problems in providing a supply of potable water for the city of Honolulu on the island of Oahu, is the determination of just how much fresh ground-water can be pumped without drawing the undesirable salt water into the deeper wells. And finally salt water in varying concentrations is found in many localities far inland. The problem of salt-water contamination in these inland localities probably involves considerations of paleo-oceanography rather than present-day oceanography, but some of the factors and principles involved doubtless are the same as those involved in coastal areas.

It perhaps need be only mentioned in passing that the ground-water hydrologist must know when he is dealing with water from the ocean as shown by certain distinctive chemical characteristics in contrast to waters of high mineral-content that have different origins.

It is, of course, well known that where bodies of fresh and salt water are in contact, because of the difference in density the fresh water floats, as it were, on the heavier salt water. Applying this principle to the occurrence of ground-water along sea coasts, with the simplest condition, that of an island or peninsula underlain by homogeneous permeable material, if the altitude of the water-table is known, the depth to the contact-zone of salt and fresh water may be determined more or less accurately. The relation becomes more complicated if some of the water-bearing beds, or aquifers, are overlain by relatively impervious beds which prevent free access of the salt water at any point along the shore and allow it to enter the permeable beds only at their sub-oceanic outcrops. Whether the aquifers are entirely filled with fresh water to their sub-oceanic outcrop or whether they are partly filled with salt water depends upon whether the head of the fresh water is sufficient to balance a column of salt water equal to the depth of the outcrops. And if there is any outflow of fresh water into the ocean its head must be even greater by an amount equal to the loss of head necessary to overcome the friction involved in flow through the beds. The idea seems to have been rather generally held that wherever fresh water is encountered below sea-level in wells near the coast there must be escape of fresh water into the ocean, but a consideration of these relations leads to the conclusion that this condition need not necessarily exist, and in fact such oceanward flow of fresh water may not be as common as is generally supposed.

The ground-water hydrologist naturally is interested in any information he can obtain from the oceanographer bearing on the origin, character, distribution, and structure of the beds that constitute water-bearing formations, whether they are near the ocean or far inland; but he is especially concerned with these factors when it becomes necessary to consider whether the geologic conditions favor the easy access of the salt water of the ocean to the fresh-water-bearing horizons. Are the beds offshore so homogeneous and permeable that the salt water can enter them anywhere along the marginal beach-zone or is there an impervious layer which effectually shuts out the salt water from the aquifer except where it crops out at a greater or less distance offshore; or perchance, does the aquifer pinch out offshore with no sub-oceanic outcrop so that the salt water can not enter it? Where permeable water-bearing sands have been proved to cover large areas with more or less uniform character and thickness it is, of course, reasonable to assume that they extend for some distance offshore. But can we, for example, assume that along the Atlantic coastal plain artesian water-bearing beds continue as permeable formations as far out as the edge of the continental shelf some 75 or 100 miles distant?

The only very definite information that bears on these questions is obtained from the charts of the oceanographer which show depths to the ocean-bottom and accordingly also the nearest possible place where the water-bearing formations can crop out if they continue oceanward without significant change of dip. It seems possible, however, that under some conditions the hydrologist can make a fairly good guess at least as to the presence or absence of sub-oceanic outcrops. For example, in certain localities on Long Island the observed hydrostatic head of the fresh water in deep-lying formations is not sufficient to push back salt water to a possible sub-oceanic outcrop at an elevation below sea-level equal to or greater than that of the bottom of the wells. This fact suggests that if there is a sub-oceanic outcrop it must be at an elevation below sea-level less than that where the formation is tapped by the observation-wells.

The occurrence of tidal fluctuations of the water-level in wells along sea-coasts has been known for many years, but until recent years this phenomenon has attracted only passing attention. Because of the necessity of interpreting fluctuations of water-levels in wells due to a variety of causes the hydrologist has a very direct interest in these tidal fluctuations and hence in the phase of oceanography that relates to the tides. Tidal fluctuations in wells conceivably may be developed in three ways. First, presumably they may be caused in the same way as earth-tides, by direct attraction of planetary bodies on the water in the observation-wells. Continuous observations have been made in many wells in inland localities in the United States, but no tidal fluctuations have been found, and if they occur the amount of fluctuation must be so small that it can be neglected.

The second and most obvious manner in which tidal fluctuations of ground-water may be produced is by the influence of the ocean-tide where the water of the ocean has free access to the water-bearing beds and imparts the tide-impulse directly to the water in the beds either at the shore if water-table conditions exist or at the sub-oceanic outcrop of the aquifer if artesian conditions exist. For reasons that can not be considered here it seems probable that the ground-water tidal impulse can not travel far from its point of origin and hence not far from a sub-oceanic outcrop.

In some areas, for example, in the Atlantic City Region and on Long Island, from a consideration of the geologic conditions it appears that the sub-oceanic outcrop of certain deep-lying aquifers, if they do crop out offshore, must be so far out that the ground-water tide-wave from that point can not be transmitted to the shore because of interference with preceding and succeeding waves. Nevertheless, the head in observation-wells penetrating such formations showstypical tidal fluctuations. The high and low tides in the observation-wells occur at about the same time as the ocean-tide, and much later than the time when it passes the supposed sub-oceanic outcrop. This fact and the similarity between the curves of the well- and ocean-tides during peculiar tide-changes indicates that the tide in the well is the result of some quite local condition, and is not transmitted underground from the outcrop. The only possible explanation appears to be that the aquifer is compressible and responds to changes in pressure transmitted from the ocean-bottom near shore through many feet of sand and clay overlying it as water is alternately piled up and removed. To this extent the observations throw considerable light on the phenomena of compressibility and elasticity of water-bearing formations as described by Meinzer in another paper of this symposium.

From these brief remarks it will be seen that the ground-water hydrologist has a very definite interest in certain phases of oceanography. Unfortunately, the hydrologist is able to offer little in return to the oceanographer. He can demonstrate that in many localities fresh ground-water from the land flows into the sea. Conceivably this supply of fresh water may have some small influence on the character of the ocean-water, and hence of the biologic conditions, near the point of emergence on the ocean-bottom; but in view of the vastness of the oceanic reservoir into which fresh water is poured and of the fact that it is almost constantly being stirred up, except in very restricted areas, as in lagoons, this factor is probably of little significance.

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OCEANOGRAPHY AND HYDROLOGY: MONTHLY AVERAGES OF SURFACE CURRENTS ALONG THE COAST OF CENTRAL CALIFORNIA COMPUTED FROM TEMPERATURES

G. F. McEwen

Let R equal the rate at which solar radiation penetrates the surface of the sea, and b equal its absorption-coefficient, which is an average value pertaining to the total energy of radiation. Then if the rate of loss of heat due to evaporation, conduction, convection, and back radiation from the surface is proportional to the surface-temperature θ, the constant being k, the following fundamental differential equation of temperature can readily be derived:

$$d\theta/dt = + Rbe^{-by}/\sigma - k\theta \qquad (1)$$

where t = time and σ = specific heat = approximately 1, and y = the depth.

Table 1--Amount of solar radiation penetrating the sea-surface, resulting rate of evaporation, and that determined by means of evaporation-pans

Latitude	$5.83\,[1 + f_3(x)]$ computed from		(1)	(2)	Computed evaporation		Determination of evaporation by	
	Temperature	Radiation	0.0325	0.0325			Wüst	Cherubim
°	(1)	(2)	(3)	(4)	(5)[a]	(6)[a]	(7)	(8)
20	8.20	7.28	252	224	0.129	0.1149		
22.5	8.00	7.15	246	220	0.125	0.1129		
25	7.62	6.97	235	214.8	0.120	0.1102	0.096	0.117
27.5	7.19	6.62	220	203.8	0.113	0.1045		
30	6.70	6.26	206	192.6	0.105	0.0988		
32.5	6.28	5.98	193	184	0.098	0.0944		
35	5.83	5.83	179	179.5	0.091	0.0921	0.080	0.096
37.5	5.32	5.56	164	171.4	0.084	0.0879		
40	4.70	5.26	144	161.8	0.074	0.0830		
42.5	3.80	4.99	117	153.6	0.059	0.0788		
45	2.92	4.62	90	142.1	0.046	0.0729	0.058	0.069
47.5	2.34	4.34	72	133.5	0.037	0.0685		
50	1.94	4.14	59.7	127.4	0.030	0.0654		
52.5	1.87	3.76	57.5	115.6	0.029	0.0593	0.033	0.039

[a]These values should be reduced by a "Bowen ratio" of about 10 to 20 per cent to allow for surface-cooling by convection and conduction.

For mean annual values $d\theta/dt = 0$ and we have

$$R = k\theta/be^{-by}$$

where the value 3 meters may be adopted for the mid-depth of layer in which mixture is so effective that the temperature-gradient may be neglected.

Using a base-latitude 35° gives

$$R = k\theta/be^{-3b} = 5.83/0.0325 = 179$$

or about 59 per cent of 304 the incident value in gram-calories per square cm per day. The amount of this penetrating radiation for any latitude is the product of 179 by $[1 + f_3(x)]$ where x = distance in degrees from the base-latitude and the function $f_3(x)$ can be estimated either from mean annual normal-temperatures or mean annual values of the incident radiation.

The expression $5.83[1 + f_3(x)]$ is computed by both methods and entered in columns (1) and (2) of Table 1, and division by 0.0325 gives the corresponding values of the penetrating radiation entered in columns (3) and (4). Using 585 for the latent heat of vaporization results in the factor 0.000513 for converting this penetrating radiation into evaporation in meters per month, columns (5) and (6). To allow for conduction and convection these values should be divided by (1 + r) where r equals the "Bowen ratio," which is about 0.1 or 0.2 corresponding to these conditions. More direct determinations, based upon evaporating-pans, of the average rate of evaporation in meters per month are entered in columns (7) and (8) for comparison.

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RELATION OF SEISMOLOGY TO HYDROLOGY

N. H. Heck

At first sight hydrology and seismology do not appear to be closely related except in the general way that existing ground- and surface-water conditions in many regions are related to geological events in the past which were accompanied by earthquakes. However, no one who has read the chapter in Hobbs' "Earthquakes" on the derangement of the surface and underflow of water can fail to realize that there are important relations. I will also point out some problems in regard to which the seismologist and hydrologist might well get together. In discussing the subject I will make frequent reference to actual occurrences.

The most obvious relation is the effect of earthquakes on the ground-water of a region. This has often been observed. In the Attica, New York, earthquake of August 12, 1929, with no rain the reservoir filled while in a region not far distant the wells went dry. In the October 8, 1865, earthquake in the San Francisco Bay Region, certain streams greatly increased their flow while artesian wells in the Santa Clara Valley were either greatly reduced in flow or ceased to flow. In certain great earthquakes, as the New Madrid, Missouri, earthquake of 1811, the whole surface-relations were entirely destroyed and adjustment had to take place over large areas.

In some cases there is no surface-indication except the change in the flow of water and this is usually where rock-layers approach the surface, but in most cases there are other changes. In the East Bengal, India, earthquake of July 8, 1918, sand and water issued in spurts from a tennis court, changing its level surface to a series of mounds and hollows. In many cases the pressure forces the ground-water to spurt upward through holes in the ground. This is evidenced by the presence of so-called craterlets in many regions, notably in the New Madrid Region and that of the Charleston, South Carolina, earthquake of 1886.

A craterlet is a ring-shaped mound of sand surrounding a depression in the center of which is a shaft usually filled with sand. This is specially evident in the New Madrid Region where the shafts are known to be in some cases from 10 to 20 feet in length, the sand lying below other formations. Hobbs states that in some cases the mounds were seven feet high, and some which were three or four feet high and 20 to 100 feet in diameter.

The method of formation of these is of interest. In many cases the water undoubtedly rose in the form of geysers, but this does not necessarily explain the craterlets. In discussion with Philip O. McQueen, Superintendent of the McMillan

filtration-plant in Washington, he told me of a phenomenon that he had observed. On one occasion there was back pressure on the filtration sand-beds and water forced its way through the sand and started small swirls of very little height, which built up sand-rings like miniature craterlets.

There are in some cases considerable effect on the surface-water. The formation of Reelsfoot Lake and many others at the time of the New Madrid earthquake and the changes in the St. Francis River show what can happen on a large scale. In the Runn of Cutch, India, earthquake of June 16, 1819, dry rivers with sandy beds filled to their brinksand wells overflowed. In the Sonora, Mexico, earthquake of May 3, 1887, there was an outburst of water through fissures and holes in the bed of the San Bernardino River at a time when the water was usually not visible. In the Owens Valley, California, earthquake of March 16, 1872, the Owens River, a fairly deep and swift stream, went dry for several hours. Permanent changes are sometimes noted in stream-beds, chiefly in delta-regions. Also streams are frequently dammed so as to form lakes. A minor example is the Montana earthquake of June 28, 1929.

In a region such as the San Andreas Rift, numerous long, narrow lakes are found.

Landslides are of common occurrence in connection with earthquakes since material which lies near the angle of repose will show sliding. This may occur both in rock and in softer material. In both cases the presence of water may be an important factor in reducing the cohesion. In several earthquakes the earthquake has removed a barrier which held back a swamp and a mud-flow has resulted. This occurred in California in 1906 and is reported to have occurred in an early earthquake in Nicaragua. In the Kan Sou, China, earthquake of December 16, 1920, the greatest landslides ever known involving mountains, have been due to the penetration of water into loess.

In Freeman's book "Earthquake damage and earthquake insurance," in a quotation from the Dewell-Willis report of the Santa Barbara earthquake the following interesting statement is made: "The nature of the ground affects the destructive intensity of earthquakes. In loose, dry ground, the initial push may be damped to some extent, but the soil is liable to shake down in the following vibrations. In loose, water-filled ground the initial shock is transmitted in full force and the subsequent shaking is of large amplitude." It is evident that the water-content of the soil is a factor that must be taken into account in designing buildings to resist earthquakes.

Water in the soil may explain one of the greatest puzzles of the seismologist--the existence of so-called gravity-waves. The problem is this. Ordinary surface-waves in an earthquake travel about 2.5 miles per second,which is far more rapid than the eye can follow. In an investigation described in the Bulletin of the American Association of Petroleum Geologists for December, 1932, an article by O. C. Lester shows that in an aerated surface-layer the velocity may be as low as 550 feet per second, though he states that the presence of water may increase this. This is still very rapid compared to the swells of the ocean to which the gravity-waves are often compared by observers. These rarely travel more than 85 feet per second. Waves traveling faster than this could undoubtedly be seen, but there is considerable difference between the highest speed water-wave and the lowest speed earth-wave. The reports of observers are in general as follows:

In the New Madrid earthquake the Earth's surface was reported as raised in great undulations, the crests of which soon parted, with resulting cracks 600-700 feet long through which sand and water spurted. Similar great undulations were reported in the Calabria, Italy, earthquake of February 5, 1783. In the greatest known earthquake, that of Assam, India, of June 12, 1897, an observer stated that the ground was thrown into violent waves as though composed of soft jelly. In the Puerto Rico earthquake of October 11, 1918, a sugar-mill superintendent made careful observations of waves which he estimated to be one meter in length and 15 centimeters high, traveling faster than a train. At Mayaguez waves were reported to be 30 meters long and 30 centimeters high. The evidence in favor of these waves and their very existence is not yet satisfactory to seismologists but it is very curious that they are not reported in all great earthquakes, and everywhere they have been reported as great, the ground-water has been near the surface and in many cases has spurted through cracks stated to have been caused by the unsuccessful attempt of the Earth-surface to adjust itself to the

form of the passing wave. I would like to see some work done by geophysical methods with the sole purpose of finding the lowest possible speed of waves in water-soaked soil.

A matter not so important to the hydrologist, but yet of interest, is the temporary effect of earthquakes on lakes and rivers. Reports indicate that the Mississippi River temporarily reversed its flow at the time of the New Madrid earthquake and that a wave of considerable vertical height swept over the banks so as to carry trees into the River. The ordinary effect is undoubtedly the production of a seiche or vibration of the mass of water in its own period. Prior to the development of instruments, lakes formed the most sensitive recorders of distant earthquakes. The outstanding case is the motion noted in a Scandinavian Lake at the time of the Assam, India, earthquake 4,300 miles away.

This discussion has been far from exhaustive. Other relations could be described and supported by examples. However, it has been shown that the fields of hydrology and seismology meet in such a way as to afford a number of interesting problems.

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GEOPHYSICAL INTERPRETATION OF GROUND-WATER LEVELS

Oscar E. Meinzer

The theory of rock-pressure as a cause of artesian-head dates back at least to early Grecian times. Thus the philosopher Thales, about 600 B.C., taught that the springs derive their water from the ocean through subterranean channels and that the water is lifted to the springs by rock-pressure. The theory of rock-pressure has had a number of recent advocates, chief among whom was the British geologist, J. W. Gregory, but apparently no effective attempt was made by any of them to apply critical data to the problem. In general, geologists and hydrologists have rejected rock-pressure as a vague heresy and have assumed that the artesian formations function as perfectly rigid and inert containers, not recognizing the fact that the data in regard to the performance of wells appear to conflict with such an interpretation.

Several years ago I undertook a study of this subject (O. E. Meinzer and H. A. Hard, The artesian-water supply of the Dakota sandstone in North Dakota, with special reference to the Edgeley quadrangle, Water Supply Paper No. 520, 73-96, 1925; O. E. Meinzer, Compressibility and elasticity of artesian aquifers, Econ. Geol. v. 23, 263-291, 1928), and I believe it has not been demonstrated that artesian formations and the overlying confining-beds are not perfectly rigid, and that the extent to which they yield to stresses may be recorded by fluctuations of the water-levels in wells that tap these formations. In other words, it appears that the water-levels fluctuate not only in obedience to the laws of the physics of the ground-water but also in obedience to the laws of the physics of the rock-formations.

Fluctuations in water-levels in wells that tap artesian formations produced by the ebbing and flowing of ocean-tides or the passing of railroad trains may be regarded merely as curious phenomena, but in fact they record the extent to which the rock-formations yield to relatively small but definitely measurable forces. Changes in atmospheric pressure, which affect the entire land-surface, are also definitely measurable. Apparently they also produce deformations of the rocks that influence the fluctuations of the water-levels in artesian wells, but the interpretation of these influences is somewhat complicated. Thus if the confining bed of an artesian formation is perfectly air-tight and perfectly rigid the fluctuations of the water-level produced by atmospheric changes will be exactly those of a water barometer--the movement of the water-level always being in the opposite direction from that in a barometer of the usual construction. If there is reason to believe that the confining bed is air-tight and yet the atmospheric fluctuations in the artesian wells are definitely less than 100 per cent, the conclusion would appear to be warranted that the difference is due to rock-deformation.

When a flowing well is allowed to discharge or pumping is begun on a non-flowing well, a cone of depression is developed. The drawdown and recovery of artesian wells appear to furnish quantitative data relative to rock-deformation. For example, when a flowing well is shut down or pumping is stopped on a non-flowing artesian well, considerable time generally elapses during which the artesian pressure is built up to its normal value. During this period, which may amount to several hours or several days, a cone of depression exists, with a hydraulic gradient from all directions toward the well, indicating that water is flowing into the part of the formation surrounding the well. From the discharge of the well before it was shut down and successive measurements of the artesian pressure, it is possible to compute the amount of inflow and, hence apparently, if there is no leakage, the amount of lifting of the overlying formation.

When a flowing well is opened or pumping is begun on a non-flowing well, the head first goes down near the well and then the drawdown-effect progresses in all directions until eventually a condition of virtual equilibrium is established. Numerous mathematical studies have been made of the cone of depression, but so far as I am informed, little attention has been given to the rate of progression of the drawdown-effect and the basic principles that determine the rate of progression. If an artesian formation were entirely rigid and water were entirely incompressible, the drawdown-effect would, I suppose, be transmitted instantaneously. In fact, however, its velocity is greatly dampened by the volume elasticity of the water itself and by the elasticity of the artesian formation, both of which involve transfer of water toward the well. Under water-table conditions so much transfer of water is involved in the development of the cone of depression that the drawdown-effect progresses relatively very slowly. Some observations on the rate of progression under artesian conditions have been made by D. G. Thompson and H. C. Barksdale in New Jersey and by Thompson in Arkansas. Two investigations at present in progress in the United States Geological Survey are furnishing observational data on the rate of progression--one by L. K. Wenzel, in cooperation with the Nebraska Conservation and Survey Division, relating to water-table conditions in the Platte River Valley; the other by R. M. Leggette and L. K. Wenzel relating to artesian conditions in the Ogden Valley, Utah. The entire problem of the manner and rate of progression of the cone of depression is apparently a difficult problem in geophysics. It involves the physics both of the water and of the rock-containers. It is of undoubted importance in hydrology and may prove to have considerable significance in other fields of geophysics.

In conclusion, the United States Geological Survey now has about 115 automatic water-stage recorders in operation on observation-wells, and a good many additional recorders are in use by other investigators. These recorders are becoming the principal instruments of precision in ground-water hydrology. They register accurately the almost constant fluctuations of the water-levels that occur in response to changes within the water-bearing formations, and under certain conditions they apparently give a measure of the rock-deformations under known stresses. It is impossible to say whether this hydrologic approach to problems of the physics of the solid Earth will lead to valuable results, but the subject would seem to be worthy of adequate investigation.

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Washington, D. C.

ASSOCIATED PROBLEMS OF HYDROLOGY AND TERRESTRIAL ELECTRICITY

O. H. Gish

The metes and bounds of hydrology define a vast domain. The sky seems to be the only limit. In defining the realm of electrology, that limit is omitted. But terrestrial electricity as here considered is restricted by about the same boundary as hydrology.

The principal subdivisions of terrestrial electricity are atmospheric electricity and earth-currents. Atmospheric electricity presents two general aspects, one in fair weather and the other in storm. In fair weather a negative electric charge resides on the Earth. Positive ions in the atmosphere are attracted toward the Earth

and negative ions are repelled. The destination of the negative charge thus repelled from the Earth, or the origin and source of supply of the negative charge of the Earth are not yet known. This is the most fundamental unsolved problem of atmospheric electricity. The ions in the atmosphere over land are continuously produced in part by radioactive matter in the Earth, but chiefly by emanations which have escaped from the Earth into the atmosphere. Those in the air over the oceans and some other regions are produced almost wholly by the cosmic radiation. However, the gross features of fair-weather electricity are much alike everywhere on the Earth, namely, a negative charge on the Earth, a positive current from the air to the Earth, the potential of the air positive with respect to Earth, and, near the Earth, increasing at the rate of about 100 volts for each meter increase in height.

This fair-weather electricity is influenced by the amount of water-vapor in the air. Wet air is generally a better insulator than dry air. This apparent paradox is largely resolved when one recalls that electricity is transported through air only by ions. Water-vapor either increases the size of ions, or in some other way makes them less mobile and hence less effective in transporting electricity. The solid and liquid phases of water exert an influence on fair-weather electricity. A blanket of snow or a sheet of water, and even water in surface-layers of the soil, obstruct the escape to the air of emanations from the radioactive matter in the soil, thus reducing the conductivity of the air and changing the electric field and the air-to-earth current to values which approach a new state of equilibrium. The rise and fall of the ground-water level by affecting the rate of egress of emanation from the soil may also produce similar effects. These hydrologic features require consideration, especially when attempting to interpret the changes in fair-weather electricity.

The storm-aspect of atmospheric electricity is very directly dependent on water. The snow and rain which fall to the Earth are charged, sometimes positively and again negatively. Large charges are developed in the clouds; the electric field of these is generally great in comparison with the fair-weather fields. The electrometers used for recording the strength of such fields at the Earth's surface show rapid and irregular changes, which are frequently 100 times that registered in fair weather, even when the clouds in which the charges develop are at a distance of several kilometers.

A separation of electric charge occurs when water-drops are disrupted or when snow-crystals are broken. By this process the spray of waves and that of waterfalls becomes charged, but it is in thunder-storms that the most striking results are produced, not alone by this but also by other processes in which water-drops are involved. The strong ascending air-currents break up water-drops repeatedly. The small drops which result from such a disruption carry a charge of opposite sign to that on the large ones. Which is positive and which negative is an important question which cannot be answered categorically. The air-currents carry the smaller drops to higher levels, while the large drops lag behind or fall toward the Earth. The process may, and often does, continue until the electric pressure becomes so great as to break down the atmospheric barrier and the lightning-flash redistributes the charge. This broad outline will, it is hoped, show the important rôle which water occupies in the process by which the electricity of thunder-storms is generated. According to one hypothesis, the thunder-storm is the principal source of the general features of atmospheric electricity and may contain the mechanism which supplies the negative charge of the Earth. On that view, water is fundamental in the whole of atmospheric electricity and the problems presented by the electric phenomena of the lower atmosphere are all largely problems of meteorology and hydrology. Although other hypotheses postulate other important influences, yet it is to be expected that interesting relationships between hydrologic and atmospheric-electric phenomena will be revealed as the sciences of these phenomena advance.

The electric currents within the Earth, briefly termed earth-currents, consist largely of systems which are quite independent of the atmospheric-electric phenomena. Systematic study has been made chiefly of those systems of earth-currents which are closely related to changes in the Earth's magnetism. These can best be described by considering two aspects separately, one the normal earth-currents, and the other the so-called "earth-current storms." The term storm in this use has no reference whatever to weather-conditions. Earth-current storms first became manifest on telegraph-lines, where ground return-circuits were used. They are a frequent source of disturbance to telegraph-traffic. During these "storms" the current usually fluctuates rapidly in an irregular manner, reverses direction, and reaches intensities as much as

a hundred times the maximum for the normal earth-current. Many of these storms are world-wide in character, occurring nearly simultaneously everywhere.

The normal earth-currents run a fairly regular course during the day. The character of these circulations of electricity in the Earth's crust may be visualized as follows: Consider the surface of the Earth divided into eight equal sectors by the plane of the Earth's equator and two mutually perpendicular meridional planes, one of which passes through the Sun. In each of these sectors an extensive whirl of electricity circulates about a center located somewhat outside the torrid zone. The direction of this rotation is opposite in any two adjacent sectors. The entire system is fixed with respect to the Sun, so that it has an apparent motion relative to a point on the Earth's surface. Thus the direction and intensity at a given place change periodically during each day. The intensity of the current which circulates in the four sectors on the daylight-side is much greater than on the dark side. Around midday in the northern hemisphere the lines of current-flow converge from the north, flow southward, and diverge as the equator is approached. In the southern hemisphere the flow is in the reverse direction, but similar in other respects.

Although such a picture is helpful, it is far from exact, even with the further elaboration required by changes in the elevation of the Sun. The circulations in the dark sectors depart from this scheme more than do those in the daylight-sectors. Overflow, so to speak, from the intense daylight-sectors into the night-sectors, distortions due to the heterogeneity of the Earth's crust, as well as other factors, doubtless produce departures from the theoretical model. The effect of such factors must be investigated in order to generalize from the observations. The conductivity of the crust varies considerably from place to place and hence local differences may be expected in the earth-currents. Water plays an important rôle here, for the Earth conducts electricity chiefly by virtue of the electrolytes there present. The conductivity of some types of soil may vary several orders of magnitude between wet and dry seasons. It is then important to know whether such effects extend deep enough to introduce seasonal or other periodic variations in the measurements of earth-currents, even for the case of periods as long as 10 or 20 years. Information about the extent and character of the more permanent conditions of the soil in regard to moisture-content, and the nature of the soil-solutions, enable one better to select a location for such measurements and more correctly to interpret the results.

If it is correct to consider the oceans a hydrologic feature, then it may be said that here is perhaps the most far-reaching contact between hydrology and earth-currents. Of all the abundant constitutents of the outer shell of the Earth, sea-water is by far the best conductor of electricity. The oceans are easily one hundred-fold better conductors than the continents. The influence of the depth, extent, and configuration of ocean-basins on the character of the general systems of earth-currents is therefore great. Much distortion, especially at continental borders, is to be expected. A quantitative estimate of these influences on the general systems of earth-currents is difficult, but is required in order to arrive at a better understanding, not alone of earth-currents, but also of terrestrial magnetism.

Earth-currents of a local nature arise from electrochemical action between the soil-constituents. Currents of such origin apparently play a part in the corrosion of steel structures which are placed in the Earth. (The currents which stray from power-systems are excluded from cases here considered.) This aspect has been most clearly shown by investigations of the corrosion of long pipe-lines. The currents between points where the soil presents contrasts accelerate corrosion by electrolytic action. Moisture is one of the factors which give rise to the contrasts and intensifies the electrolytic action.

The "self-potential" method of prospecting for certain types of ore-bodies, notably the sulphide ores, utilizes a phenomenon of this character. The results of such explorations doubtless depend very much on hydrologic conditions.

Another phenomenon which may be of a character similar to those just described has been interpreted to indicate a class of earth-currents which always "flow up-hill." Thus, measurements of potentials on the various slopes of a mountain, with few exceptions, show that a point at a high elevation is at a lower potential than points farther down the mountain. It is then concluded, by some, that current flows in the

Earth from a point of higher to one of a lower potential, that is, from the base toward the summit of the mountain. Such an interpretation, however, presents an anomaly, because no plausible means of completing the circuit can be found. The currents implied in such an interpretation would probably be more than a million times that which is measured in the air over mountain-tops. Yet this is the interpretation which writers on the subject often entertain. Some think that this and some other apparent vertical earth-currents, which magnetic measurements may be taken to indicate, may be the result of an as yet unknown fundamental physical principle or element, and that this and similar phenomena may in time bring to the attention of the physicist new fundamental elements or principles just as the cosmic rays have directed his attention to protons of extraordinary penetrating power, electrons of exceeding swiftness, and a formerly unknown element of atomic structure--the positron. Such surmises may be justified, if the interpretation here described is the correct one. Emphasis is placed on the "if."

But it does not necessarily follow that an electric current is flowing wherever a difference of potential is measured between two points of the Earth. A difference of potential exists between the terminals of a battery when no current is flowing. Circumstances which simulate such a battery may be found at many places on the Earth. In fact, it is difficult to avoid them. For example, a difference of potential is likely to exist between a wet spot of earth and the surrounding dry area, but a flow of current is not a necessary consequence. This phenomenon of earth-currents which have a predilection to flow "up-hill" deserves thorough investigation, especially from the viewpoint here suggested, in order to avoid trying to explain something which may not exist.

There are reasons and some evidence for thinking that the top of a mountain acts as the negative pole of a battery. The leaching action of water, on hillside or mountain-slope, apparently carries the more soluble alkaline constituents from higher to lower levels. This action alone may be sufficient to give rise to a phenomenon of this character. However, it is believed that other hydrologic features, such, for example, as the distribution of soil-moisture with altitude, may require examination.

Ocean-currents, tidal motion, the flow of streams, may be expected to generate electric currents by the motion of water across the Earth's magnetic field. Faraday expected and sought for such an effect in the River Thames, but his only conclusion was that the errors inherent in such measurements are greater than the effect he was seeking. Measurements made in England during the war definitely showed the electrical effects of tidal and wave-motion. The electromotive forces generated by ocean-currents have never been investigated but they doubtless exist. It is calculated that the Gulf Stream, off the coast of southern Florida where the velocity is greatest, may generate an electromotive force of 80 mv/km. This would result in a current-density much greater than that of the general world-wide systems of earth-currents. Such a current would be unidirectional, whereas the general earth-currents reverse one or more times each day.

An electric current flowing in an electrolyte, such as sea-water, does so by the transference of ions. Even though the current-density be very small, the electrolytic effects accumulated through the ages may be of some importance in aspects of oceanography, geology, and mineralogy. For example, it is estimated that the density of the electric current which may flow across the Gulf Stream is such that one gram of the gold ions in sea-water is moved across each square centimeter of cross-section in about 3,000 years. It may be some consolation to learn at this time that the movement of this gold is toward the United States!

From this brief review of the relations between hydrology and terrestrial electricity it is doubtless evident that a number of hydrologic features affect the electric phenomena of the Earth and the atmosphere; the converse relation, however, seems to be as inconspicuous in nature as it has been in this review.

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PROGRESS-REPORT ON THE ABSOLUTE DETERMINATION OF GRAVITY AT WASHINGTON

Paul R. Heyl

(Abstract)

The absolute determination of gravity at Washington has reached the last stage--that of accumulating the observations necessary to give the final result. Four silica pendulums are to be swung on three agate knife-edges, making a total of 12 determinations of gravity, each requiring, with the necessary length-measurements, from two to three weeks. Of these 12 units three have been completed. This is not sufficient to give any estimate of the final result, but it appears that the figures at present obtained are somewhat lower than those derived from the connection with Potsdam.

U. S. Bureau of Standards,
Washington, D. C.

NEW GRAVITY-CONNECTION WITH POTSDAM, GERMANY

Edwin J. Brown

Any gravity-work which has to do with the comparison of base gravity-stations which have been in existence for a long period of time is principally of interest when considered in the light of the past history of the stations. It is particularly interesting to note the changes in the absolute values of gravity which have been determined at different times for the same station. The Washington base-station serves as a good example for such a study, as it has been in existence throughout the era of precise pendulum-observations.

Observations for determining local variations in gravitation were begun in the United States by the Coast Survey in 1873. Some two years later, 1875 and 1876, an observer, C. S. Peirce, was sent to Europe to compare the Coast Survey pendulums with those used in the geodetic operations of the great European surveys. Peirce's results were the basis for the first accurate determination of the absolute value of gravity at the Washington base-station, the value deduced being 980.098.

This remained the best value for Washington until 1900 when Putnam made a connection with several of the European stations, the most important of which was Potsdam, later to be designated the international gravity base-station. Putnam obtained a value for Washington of 980.111. This value was changed to 980.112 following the publication of Borass' world adjustment in 1911.

This value of 980.112 remained unquestioned until 1928 when Dr. Vening Meinesz swung his pendulums at Washington and obtained a value of 980.120. The determination made by Meinesz was not a direct connection with Potsdam but the rather large difference in the value obtained by him and the accepted value caused some concern.

In 1928 A. H. Miller of the Canadian Geodetic Survey connected the Canadian base-station at Ottawa with Greenwich and Potsdam, and followed this work by a series of observations at Washington in 1929. Miller obtained a value for Washington of 980.118. This was in accord with the result obtained by Meinesz and further indicated the probability of error in the absolute value in use for Washington.

It was accordingly decided that at the first opportunity a direct connection should be made between Washington and Potsdam. The need for such a connection was made more imperative because of the absolute determination of gravity being made at the Bureau of Standards by P. R. Heyl. In order to realize the full international significance from Heyl's work it was considered essential that his base of operations be connected to the Potsdam international base with the greatest possible accuracy.

Authorization for the Washington-Potsdam connection was granted for the fiscal year of 1933. Operations were begun during November 1932 and are practically complete at the present time.

The plan decided upon for this work consisted in swinging pendulums at both the Coast and Geodetic Survey base in the Department of Commerce Building and at the base being used by Heyl at the Bureau of Standards. The complete program of observation is as outlined below:

(1) Six pendulums, three bronze and three invar, were to be swung at the Commerce Building Base.
(2) Nine pendulums were to be swung at the Bureau of Standards, the six of (1) and three additional pendulums of bronze.
(3) The nine pendulums were to be swung at Potsdam.
(4) The nine pendulums were to be swung again at the Bureau of Standards.
(5) The six pendulums of (1) were to be swung again at the Commerce Building Base.

The Mendenhall pendulum-apparatus as developed by the Coast and Geodetic Survey is being used for the observations. This apparatus is as described in Special Publication No. 69 of this Bureau, except that the mechanically operated flash-box was replaced by a neon-tube apparatus in order to eliminate the time-errors due to mechanical operation of a shutter.

The individual swings of the pendulums are of 12 hours duration. Two knife-edges are being used, and each pendulum is swung twice on each of the knife-edges. In all other respects the observations are being carried out in the usual manner.

Flexure-corrections are determined by means of the interferometer, a measurement being made at the beginning and at the end of the swings on each knife-edge. This requires normally four flexure-measurements at each station occupied, the knife-edges being changed but once at each station.

The invar pendulums are tested for magnetism each time they are swung, and demagnetized when necessary.

For the observations in the Commerce Building time was furnished by a direct wire connection to one of the transmitting clocks at the United States Naval Observatory. This clock is compared with the standard clocks of the Observatory at each observing-period.

At the Bureau of Standards a connection was made to the Shortt clock being used for the absolute determinations. The time was taken "photoelectrically" from the master pendulum of the Shortt clock. Clock-corrections were determined by means of daily comparisons with the United States Naval Observatory radio time-signals.

At Potsdam connection was made to one of the Standard Reifler clocks of the Geodetic Institute. Clock-corrections were obtained from star-observations made by the Geodetic Institute and by daily comparison with the crystal clocks of the Physikalisch-Technische Reichsanstalt.

At the Commerce Building the observations were made in the specially constructed gravity-room used by the Coast and Geodetic Survey as a base for all field gravity-observations.

The observations at the Bureau of Standards were made in a sub-basement of the East Building, near the location of the absolute apparatus being used by Heyl.

The observations at Potsdam were made on the pier in the Ostkeller of the Geodetic Institute. The Ostkeller is one floor below the room in which the Potsdam absolute measurements were made. It is probably the same room used by Putnam in 1900, and adjoins the room in which Miller observed in 1928.

At the present time the observations are complete except for the final standardization at the Commerce Building. This work is now in progress and will be finished within a few days. No final results are available as yet but indications are that the final value will differ but little from that obtained by Miller in 1929.

In view of the indicated close accordance of results of these two independent series of observations carried out by Canada and the United States, it is probable

that an adjustment of results can be made which will give the two countries the same plane of reference for their gravity-observations. The Mexico City base-station is also connected to Washington, and Mexico will probably accept the result obtained from such an adjustment, thereby placing the entire North American continent on the same gravity-datum.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE APPLICATION OF RADIO TO ASTRONOMICAL LONGITUDE-DETERMINATIONS OF THE GEODETIC SURVEY OF CANADA

Noel J. Ogilvie

Radio was first used in 1914 by the Geodetic Survey of Canada, Department of the Interior, in connection with longitude-determinations on the upper Ottawa River. For a number of years, however, the many advantages inherent to the use of radio over the land-telegraph method were not fully appreciated and it was not until 1928 that telegraphic time-exchanges were entirely superseded by the use of modern wireless time-signals so universally employed today.

In 1914 and the two succeeding years, about 14 determinations of wireless longitudes were made in Ontario and Quebec. At that time prior to the general use of radio transmitting- and receiving-valves our receivers were of the old crystal-type employing the "cat's-whisker" detector on which the spark-signals transmitted from Arlington were received with fair regularity on a wave-length of 2,500 meters.

The receiving-antennae employed in those days were of a design and magnitude of amazing proportions. They conformed to the popular belief that the strongest, clearest, and most desirable signals would be secured by erecting a very long aerial at an elevation as close to the stratosphere as possible, limited only by the heights of the near-by trees and the climbing ability of the astronomical field party. The field party of the Geodetic Survey of Canada carrying on this work employed an aerial up to 600 feet in length comprising two multi-strand wires separated by a cross-arm at each end 13 feet in length. Several axemen were employed on the party for the purpose of clearing a swath near each observation-station in timbered country to permit of the erection of the aerial. One of the crew, a picked man, endowed with unusual courage and agility climbed the highest tree at each end of the swath. At heights ranging from 60 to 80 feet from the ground a pulley would be secured to top of the tree and the aerial system would be hauled aloft. After adhering to this practice for some time, the engineer-in-charge decided to experiment a little to prove or disprove the necessity for the elaborate antenna. One night during the five-minute period of signal-broadcast several members of the crew stood by and slowly lowered the antenna while the engineer listened on the receiver to note any variations in the strength of the incoming signals. Incredible as it seemed, at that time, no appreciable diminution of signal-strength was observed. Further tests showed that an antenna of 100 or 150 feet in length stretched 10 feet above the ground gave signals substantially equal to those received on the more elaborate antenna. Needless to say, a more economical and easily erected single-wire aerial was adopted on subsequent work.

In 1916 an unusual incident occurred proving that the advancement of science does not always meet with the approval and support of the ordinary citizen. Arriving at a certain geodetic station in New Brunswick to make a Laplacian determination of azimuth, the chief-of-party received the reluctant permission of the owner of the land on which the station was located to transport the astronomical equipment to the desired point on a wooded hill one mile distant. Later in the day, the owner appeared on the hilltop while the party was engaged in erecting the aerial. Not understanding the nature of the strange equipment and observing a few limbs lopped off a tree, he ordered the immediate cessation of all operations. Explanations and assurances that damage to property would be avoided were of no avail. Not until some time later did he finally agree to the continuance of the work. This concession, however, was made with the reservation that no aerial should be erected among his trees. Accordingly, the party was obliged to string wires from a telegraph-office a mile away and make the longitude-determination by means of the old land-telegraph method.

The results of a longitude-determination made at Emily geodetic station in 1916 by T. C. Dennis are shown below. These results were among the first determinations of longitude made by the Geodetic Survey of Canada using the old crystal "cat's-whisker" detector for the reception of spark time-signals from Arlington. The signals were also received each night by the Dominion Observatory, Department of the Interior, at Ottawa, the lag-error determined there being applied to the field results at Emily. These spark-transmissions of time-signals were used for field longitude-determinations at points in Ontario up to 1,000 miles distant from the Arlington broadcasting-station.

Date, 1916	Astronomic longitude of Emily station
June 9	$6^h\ 06^m\ 02^s.343$
13	02.360
15	02.237
19	02.308
20	02.300
21	02.296
26	02.384
July 1	02.377
2	02.437
Mean value	6 06 02.337

In connection with the establishment in 1924 of the Interprovincial boundary between Alberta and British Columbia, long-wave radio was used in making a geographical position-determination as a datum for local triangulation. The field party arrived at Sheep Creek, Alberta, after a journey of 120 miles with pack-horses through the mountains north of Mount Robson.

The radio receiving-equipment was set up on the day of arrival and the moment of signal-broadcast awaited with great anxiety. Tuning to the 17-kilocycle setting for NSS, the signals from Annapolis, 3,000 miles distant, could not be heard. The keen disappointment resulting from this failure weighed heavily on the party for the next 24 hours. The unreliability of radio was soundly denounced but preparations for star-observations were nevertheless completed. The next night at the proper time the radio receiver was again tuned in. Faintly, though sufficiently clear for observation, came the regular beats from Annapolis. The signals were successfully received by the vernier clock-method on that and on seven succeeding nights when the work was completed and the return trip undertaken. On the homeward journey the pack-horse carrying the radio equipment slipped and fell on the mountain-trail. Crashing down a hillside, it plunged into a turbulent mountain stream from which it was eventually rescued. The radio receiver was found reduced to a heterogeneous mass of assorted parts on the bottom of the wooden container. This long-wave receiver consisted of one stage of tuned radio frequency, a regenerative detector, and three stages of transformer-coupled audio amplification. Peanut tubes having a low battery-drain were employed.

In 1928 a short-wave receiver was first used on this Survey. For work on the Ontario-Manitoba boundary and on the establishment of the 60th parallel of latitude at the northern limit of Manitoba on the Hudson Bay coast a three-tube short-wave receiver gave fairly consistent results. Several times throughout the season the signals were missed when a more sensitive receiver would have given reception adequate for accurate vernier-observation.

The following year a receiver of slightly superior design was used for further work on the Ontario-Manitoba boundary and the Hudson Bay coast. This consisted of an untuned stage of radio frequency, a regenerative detector, and two stages of audio. UX-201A tubes were used except in the radio-frequency stage which employed a UX-222. This receiver, while superior in its performance to the three-tube set, had not the added sensitivity that would be expected from the addition of the extra tube. In other words, the addition of a stage of untuned radio-frequency amplification does not seem to give much marked improvement. Another disadvantage peculiar to all regenerative short-wave receivers was the instability of the oscillations produced by the regenerative detector. Due to variations in the frequency of the autodyne oscillations or the "pulling" of the local oscillations by the incoming signal, it was usually impossible to receive the time-signals over a five-minute period without several readjustments of the tuning-controls.

When it is realized that the loss of time-signals on a clear, starry night with the consequent failure to secure a longitude-determination may result in a prolonged wait of several days till another clear night occurs, it becomes apparent that it is extremely poor economy of time and money to carry on with anything less than the best type of radio receiver that it is possible to secure. Particularly does this apply today when the most modern and perfected type of commercial superheterodyne receiver may be purchased at relatively small cost. Although the Geodetic Survey of Canada has not, as yet, any radio receivers of this type, one or two Canadian Government signal-services are using them with great satisfaction and success. Radio operators who have used many types of short-wave receivers are enthusiastic over the performance of the superheterodynes in bringing weak signals up to a readable level of intensity under adverse atmospheric conditions.

The superheterodyne receivers may be equipped with tubes suitable for battery-use and although the drain is fairly high yet it presents no serious difficulty for their use on geodetic field work. This may be readily appreciated when it is realized that they are in actual operation for a few minutes only each day during the periods of time-signal reception. Commercial type short-wave superheterodyne receivers are now manufactured both in the United States and Canada. The design usually involves a first detector, two stages of intermediate-frequency amplification, a second detector, a separate electron-coupled oscillator for the reception of continuous-wave signals, and one or two stages of audio amplification. When the receiver is to be used at points where alternating-current power may be utilized a rectifying tube and filter are usually incorporated into the set, eliminating the necessity for the use of A and B batteries.

Perfect reception of time-signals over an entire field-season is seldom, if ever, attained by officers of this Survey. It seems to be the irony of fate that radio reception in general is at its worst during the warm months of the year when field longitude-work is undertaken. Unaccountable failures of time-signals to "come through" have puzzled observers throughout the world. Electric charges in the clouds resulting from intense summer heat no doubt are partly responsible for some of the poor reception. The aurora borealis has on two occasions been observed by officers of this Survey to produce a sudden blanketing effect which completely shut off the signals from Arlington. In northern Canada where the auroral displays are quite common in the late summer and early autumn these phenomena may cause considerable slowing down of progress in this line of work. On the other hand, intense displays of aurora borealis have been observed in the north to have no appreciable effect on incoming radio signals. On another occasion when two radio receivers were in use, it was found that the blanketing effect of the aurora borealis was much less marked on the long-wave Annapolis transmissions (17-kc) than on the short-wave broadcasts. For work in remote regions in Canada it is now considered desirable to carry both a long- and short-wave receiver.

Our party working last summer in the Yukon Territory found that the long-wave (17.8-kc) signals from Annapolis could not be picked up at all while satisfactory reception was a daily occurrence from Arlington and Mare Island on wave-lengths of 23 and 35 meters approximately. The other party working in Nova Scotia had trouble occasionally in receiving the short-wave signals, due in all probability to the effect of skip-distance. By having the long-wave receiver available, it was always possible to secure time-signals on either long- or short-wave two or three times during the early evening and night and in this way be able to take full advantage of the clear weather.

Apart from the ability to secure signals on both long- and short-wave lengths, the wisdom of carrying two receivers was borne out last summer when one of the receivers used by our party in Nova Scotia developed open circuits in the audio transformers due to the absorption of moisture. The consequent spreading of the thin iron plates constituting the transformer cores caused breakages in the fine secondary windings necessitating the installation of complete new transformers. With the second receiver available for immediate use the breakdown did not cause any delay in the season's operations.

Recent practice, both commercial and amateur, in radio telegraphic communication seems to indicate more definite attention to the design of the receiving-antenna. In this connection, the tuned doublet aerial with transposed lead-in has advanced much in

favor. This type of aerial was tried last summer by our Nova Scotia party and it was found to result in a marked increase in signal-strength as well as a reduction in general noise-level. It is quite evident that a small amount of care and labor expended on the erection of this type of aerial may be well repaid by the satisfactory reception of signals on nights when they would not be received by the ordinary single-wire antenna.

Another type of receiving-antenna which is coming into some prominence is the horizontal-diamond type. While no detailed constructional data have been obtained regarding this antenna, it is known to possess marked directional characteristics. Its use with a transposed lead-in results in a high ratio of signal-strength to background-noise. It is to be realized that the use of the tuned doublet or horizontal-diamond type antenna would be resorted to only in case of inability to receive signals with satisfactory volume on the ordinary single-wire antenna.

The application of radio has so revolutionized and simplified the technique of astronomical longitude-determination that the cost of carrying on this work has been greatly reduced. At the same time the accuracy of results secured by this method has been found to equal or excel that derived by the land-telegraph method. In consequence of the important application of the radio art, both from a scientific and economic viewpoint, to the science of practical field astronomy, it becomes evident that geodetic engineers in general should keep abreast of the times in the development of this fascinating branch of modern science.

Geodetic Survey of Canada,
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FURTHER RESULTS IN THE STUDY OF APPARENT VARIATIONS OF THE VERTICAL WITH THE HOUR-ANGLE OF THE MOON

Harlan T. Stetson

Studies in the variation of latitude have been continued at the Perkins Observatory subsequent to the last report (Pub. Nation. Res. Council, Trans. Amer. Geophys. Union, 13th annual meeting, 85-88, 1932).

Following the procedure then outlined, reduction-curves have been determined for Tschardjui and Mizusawa for the years 1910 and 1911, and are represented herewith by Figures 1 and 2. These curves follow, in general, the same trend of those previously published with the principal maximum near 12^h when the moon is south of the equator, with a corresponding minimum at the same hour-angle when the moon is north of the equator. The continued inversion of phase with a change of sign in the moon's declination appears to give further evidence for a tidal phenomenon.

The mean curves for the four stations previously published for these years, Gaithersburg, Cincinnati, Ukiah, and Carloforte, are represented in Figure 3, and have been published in Nature (v. 131, 147, 1933). In this figure the solid dots represent the results of individual groups of observations, the small circles representing the running means of five consecutive points. The scattering of the observations is thus represented and there seems to be little doubt as to the reality of the curves drawn from the running means.

Some progress has been made in the reductions of these latitude stations for the other years. Preliminary studies of these reductions suggest a progression in phase which may be secular. It may be well to point out that on account of such changes a rigid harmonic analysis of a long series of observations tends to mask the effect, and may therefore account for the failure of such studies as may have been previously made in detecting so pronounced a lunar correlation as appears to result from the present treatment of the observations.

Apropos of the small changes in latitude as a function of the lunar hour-angle, A. L. Loomis of the Loomis Laboratory, Tuxedo Park, New York, called attention to variations in the time-signals determined at Greenwich and Washington, so that it seemed

worth while to investigate the possibility of the deflection of the vertical in an east and west direction from an intercomparison of the time-signals exchanged by radio between Annapolis and Rugby. A joint paper by Loomis and Stetson, presented at the Atlantic City meeting of the American Association for the Advancement of Science in December 1932, showed the results of a study of variation in time-determinations on the two sides of the Atlantic as a function of lunar hour-angle and declination. Time-signals from Rugby at 18^h G.C.T., corrected by its own error published in the Admiralty Notices, have been compared with the Arlington signals at 17^h G.C.T., similarly corrected.

With the comparisons of the time-signals the following equations result:

$$d = a + t - m$$

$$d = b - t - n$$

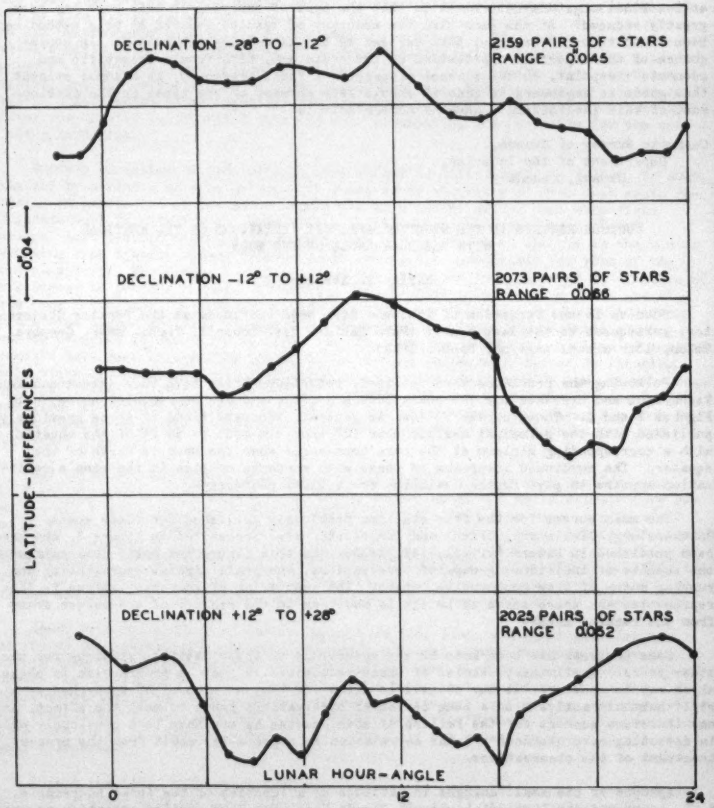

Fig. 1--Latitude-variation with moon's hour-angle and declination, Tschardjui observations, 1909-1911

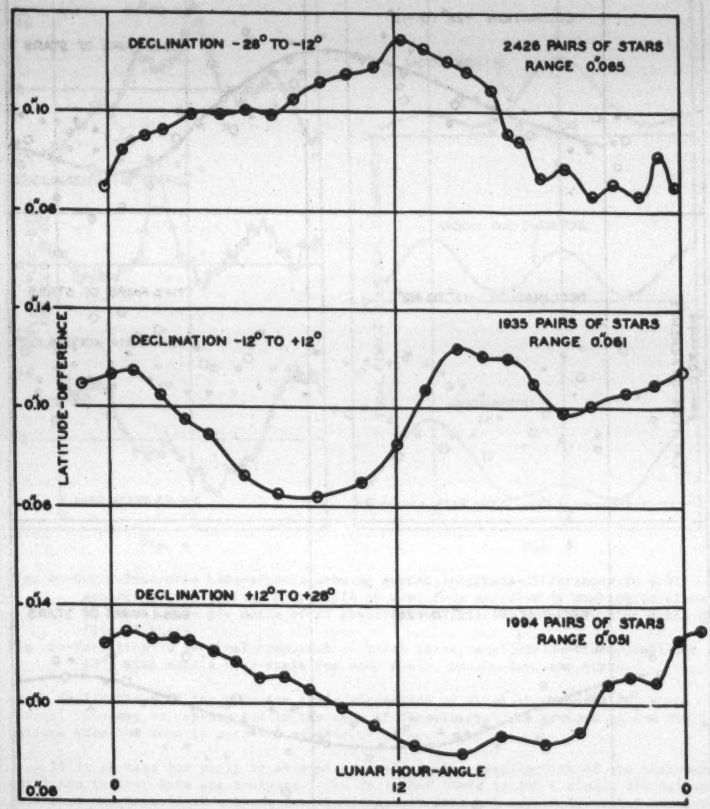

Fig. 2--Latitude-variation with moon's hour-angle and declination, Mizusawa observations, 1909-1911

where d = difference in corrected times between England and the United States, t = time of propagation of the radio wave across the Atlantic in either direction, a = Washington correction to NSS (Arlington) at 17^h G.C.T., m = Greenwich correction to NSS (Arlington) at 17^h G.C.T., b = Washington correction to GBR (Rugby) at 18^h G.C.T., and n = Greenwich correction to GBR (Rugby) at 18^h G.C.T.

The equations may be solved for either d or t. Thus

$$2d = (b - n) + (a - m)$$

$$2t = (b - n) - (a - m)$$

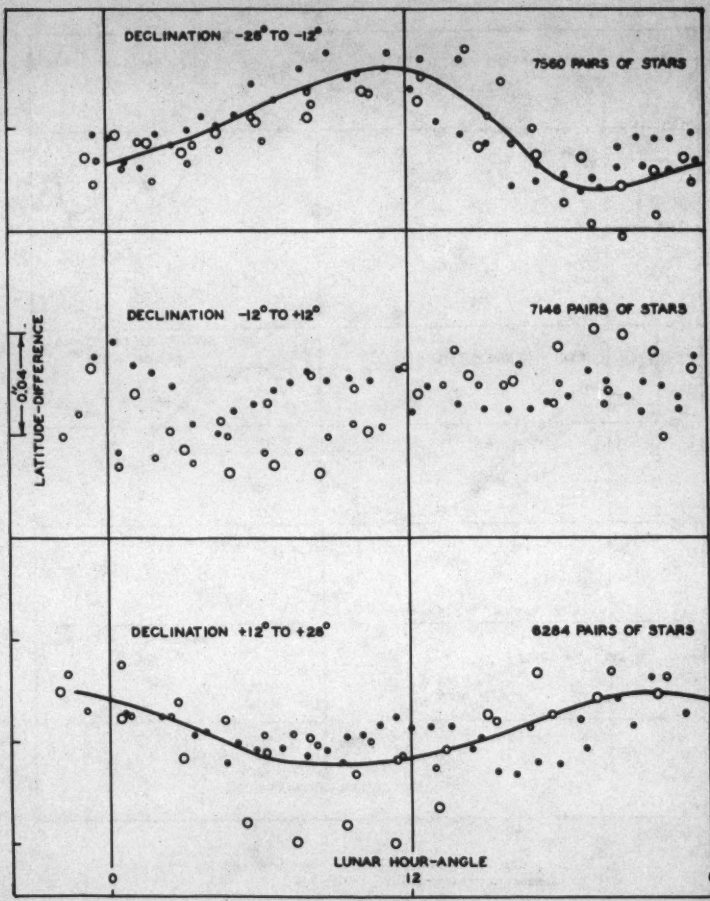

Fig. 3--Variation in latitude with the moon's hour-angle and declination, 1909-1911, from observations at Gaithersburg (small circles), Cincinnati (medium circles), Ukiah (large circles), and Carloforte (dots)

From data so obtained covering 698 days on which signals were satisfactorily exchanged, values of d were obtained which were tabulated by lunar hour-angle and declination. The curves resulting from the comparisons are represented herewith in Figure 4. The comparison of these curves, which may represent a periodic change in longitude-difference between Greenwich and Washington, shows a striking resemblance to the general form of the curves representing latitude-variation as correlated with lunar hour-angle and declination. The inversion of phase represented in the curves for north and

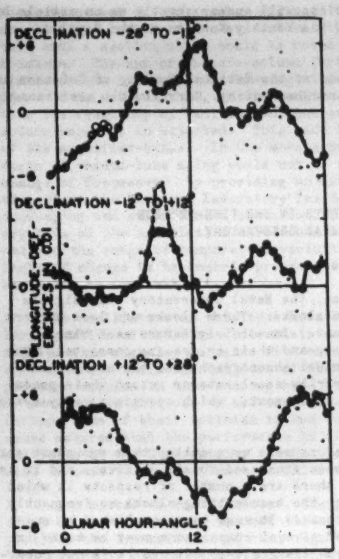

Fig. 4

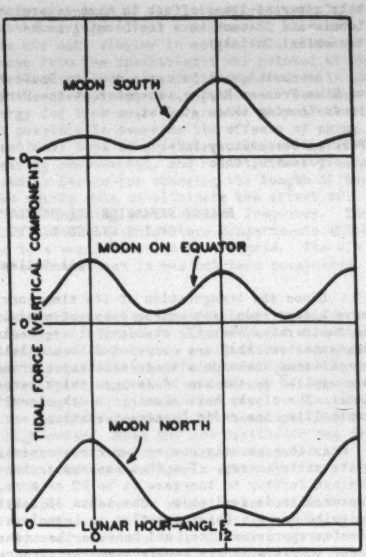

Fig. 5

Fig. 4--Rugby-Annapolis time-signals showing second longitude-differences in 0.01 second plotted against hour-angle of moon from meridian of Washington minus 12 hours; dots are means of 25 observations and circles are running means of five of these

Fig. 5--Variation in vertical component of tidal force, equilibrium-tides, latitude 40°, with moon's hour-angle for moon south, on equator, and north

south declinations of the moon are again suggestive of tidal phenomena. The semi-diurnal tide may be represented in the case of the observations grouped by low declinations when the moon is near the equator.

It is perhaps too early to attempt any satisfactory explanation of the phenomena until the further data are analyzed. The fact that there is but a single diurnal maximum when the moon is at extreme declination south does not appear inconsistent with some tidal explanation.

For comparison purposes an example of the equilibrium-tides, actually calculated for latitude 40° for another purpose, is included in Figure 5. It will be observed in this Figure that the principal maxima for declinations north and south are separated by 12 hours. An elementary examination of tidal principles shows that the form of tidal wave at any point, and the interval between maxima, may be quite irregular, being dependent upon many factors not determined in the present instance. The magnitude of the apparent variation in longitude is a serious difficulty in explaining the phenomena on the basis of any present allowable conception of earth-tides. It should be emphasized, however, that since the time of transmission of the radio wave across the Atlantic has been eliminated from the equation, the variations in t could hardly be expected to influence the values of d here discussed. A solution of the equations for the time of transmission has been made giving a value of t = 0.04. The values of t show small variations which may be periodic, but which are so small in magnitude as to appear to be of little consequence in the interpretation of d. A fuller account of

this apparent lunar effect in time-determinations will appear shortly as an article by Loomis and Stetson in a forthcoming number of the Monthly Notices of the Royal Astronomical Society.

Acknowledgment is again due the Gould Fund of the National Academy of Sciences and to Miss Frances Naylor, computer at the Perkins Observatory, for valuable assistance in furthering these studies.

Perkins Observatory,
Delaware, Ohio

RECENT EXPANSION AND DEVELOPMENTS IN THE TIME-SERVICE OF THE UNITED STATES NAVAL OBSERVATORY

Paul Sollenberger

Since the inauguration of its time-service, the Naval Observatory time-signals have always been sent out by means of pendulum-clocks. These clocks are less uniform in their rates than the standard sidereal-clocks. Immediately before each time-transmission, they are compared with the latter, and their errors are corrected. The comparisons are made with an ordinary astronomical chronograph, and the corrections are applied by the use of devices which temporarily accelerate or retard their pendulums. The clocks have electric break-circuit attachments, which operate a relay-system controlling the radio broadcast-stations.

As long as only one or two time-transmissions were made daily, this equipment was quite satisfactory. Now that the number has been increased to six or seven, and it is desired further to increase it to 20 or more, there are a number of respects in which improvement is desirable. The labor of setting the transmitting-clocks so frequently is quite large. This operation is laborious because it must be accomplished by successive approximations, and because the mean of several comparisons must be taken in order to get a single accurate value. Even with the greatest of care it is not possible to set the clocks with an error less than about three-thousandths of a second. If this error happens to be of opposite sign for signals which are within two or three hours of one another, the resulting error of rate may be of importance in some types of work. The matter is rendered much worse by the variable lag of the radio station. As a result it is not possible to do accurate work of any type except by taking into consideration time-signal corrections. In order to overcome these difficulties an entirely new method of transmitting the signals has been devised. The new apparatus necessary to put the method in effect is now nearly complete, and it is hoped that it may be installed some time this year.

The principal unit of the equipment is a Piezo-electric, crystal-controlled clock. This type of clock was originally developed by the Bell Telephone Laboratories. They have also been constructed by the General Radio Company and the Naval Research Laboratory. The original Bell Laboratory design utilized a doughnut-shaped crystal, which was cut in such a manner as to reduce the temperature-coefficient. This crystal was driven by a vacuum-tube circuit, very similar to the circuit employed in crystal-controlled radio transmission-apparatus. Since the frequency of the crystal was generally very high, it was necessary to employ circuits which generated some exact submultiple thereof. For instance, if the original frequency were one million cycles per second, it might be put through three successive submultiple generators, each of which would divide the frequency by ten, giving a final frequency of one thousand cycles. This frequency was amplified and used to drive a synchronous motor clock.

In the year 1930 Wheeler and Bower built three crystal clocks of new design at the Naval Research Laboratory. Instead of using small crystals which vibrated transversely, they employed long bar-crystals which vibrated in a flexural manner. Since the frequency of these crystals was one thousand cycles per second, no subdivision was necessary. The problem of mounting the crystals, which had previously been a difficult matter, was made simple, as it was only necessary to suspend the bars by two threads, attached at the nodes. Probably the most unique feature was the method of driving the crystal. A small amount of energy was picked up by condenser-plates near the ends of the quartz bar. This was amplified and fed into a loud-speaker unit. The

acoustic output of the speaker was used to set a column of air into vibration. In order that the length of the air-column might be varied, it was contained in a brass tube with a section which could be moved in and out, similar in action to a slide trombone. The end of the air-column farthest from the speaker-unit was pointed at the middle of the crystal, thus keeping it in vibration by means of the sound-waves in the air. It is evident that, if the length of the air-column were adjusted to resonance with the frequency of oscillation, the energy fed back would be greater than if the column were not so adjusted. This made it possible to overcome the effects of aging of the amplifier-tubes. In the more conventional type of crystal-oscillator the effects of vacuum-tube aging could not be readily compensated, and resulted in a gradual change of frequency. By providing an automatic device for changing the length of the air-column the Research Laboratory has been nearly able to eliminate the effect of tube-aging and other causes of variation, thus insuring more constant frequency. The crystals of the oscillators were contained in constant-temperature compartments which reduced the range of temperature-variation to a small fraction of a degree. The effects of change in barometric pressure are so small that it has not been considered necessary to deal with it.

The oscillators of this type have been running at the Research Laboratory for a large portion of the time since their manufacture. They have been compared with the regular time-signals, and also with one of the Bell Laboratory oscillators. As a result of these tests the builders of the new crystal clock have concluded that all previous records in time-keeping have been eclipsed, and that an accuracy of one part in one hundred million, or better than a thousandth of a second per day, is possible. Perhaps some of their optimism is due to the natural enthusiasm of inventors, but it seems assured that the performance is of high order. When the new oscillator has been delivered at the Observatory, and has been in operation for an extended period, it will be possible to draw more definite conclusions concerning its accuracy.

As a matter of fact, however, the principal reason for securing an oscillator-clock at the Observatory was not its extreme accuracy. It was because it would make possible the transmission of time-signals by a synchronous motor-driven program-device. This device is now nearing completion at the Naval Observatory instrument-shop. It is provided with means for comparing it quickly with other timekeepers, for easily correcting its error by any desired fraction of a second, without disturbing the main oscillator, and for automatically transmitting and recording time-signals at any predetermined hours of the day. In addition it will automatically record comparisons of as many as eight other standard clocks, at any predetermined times.

If at any time it is desired to make visual comparison of the program-device with any other available timepiece, it may be done by closing a switch and looking into an eyepiece. A flashing neon-lamp is placed so that it may illuminate a moving dial for such a brief time as to make it appear stationary. In this manner it will be possible to read off the time of the incoming signals with an error not exceeding one-thousandth of a second. Even if the error of rate of the oscillator-clock should be ten or twenty times as great as the makers expect, it will be necessary to reset the transmitting-device only once or twice per day, and it is hoped to be able to operate longer between such settings. When it does become necessary to apply a correction, it may be accomplished by rotating the field-coils of the synchronous motors. This may be done in a few seconds, and the amount of the applied correction will always be exactly known. It may be possible to establish some definite time of day for making corrections. In such a case, persons using successive signals in gravity- or rate-work may be able to reduce their work at once because they will know that the transmitter has not been reset in the meantime.

The program-device has been designed to perform all the operations necessary to the transmission of time-signals, including starting and stopping the recording-chronograph, and turning on the radio receivers. The frequencies to which the receivers must be tuned vary from signal to signal, which will require the presence of an operator. In order to simplify the work as much as possible, and to make possible the simultaneous recording of a number of frequencies, nine new receivers of special design have been obtained. It is not possible to secure sufficient stability on the higher frequencies to eliminate the necessity of occasional readjustments. Moreover it will be necessary to have an operator on duty at all times, in order to make necessary repairs, to send the signals by the old method if necessary, and to make sure

that everything is in good order. It is anticipated, however, that his duties will be simplified to an extent which will make possible the transmission of an increased number of signals with the present personnel.

U. S. Naval Observatory,
Washington, D. C.

THE PROGRESS OF GEODETIC WORK IN MEXICO DURING RECENT YEARS

Manuel Medina

Geodesy, strictly speaking, began in Mexico in 1899 with the measurement of the arc along the 98th meridian west of Greenwich. For this purpose there was created the Mexican Geodetic Commission, which collaborated with the United States and Canada in this international undertaking. The part of this arc which is in Mexican territory extends from Lanuyu, on the Pacific coast, to the Rio Bravo del Norte (Rio Grande), near the frontier town of Matamoros.

This work has already been fully described in reports and papers, and because of both the methods with which it was executed and of the results obtained, it has been accepted by the International Union of Geodesy and Geophysics as an international operation properly executed and finished.

The further geodetic work of the Republic has been directed toward the need of establishing a rigid net for the control of the topographic mapping of the country. It was originally proposed to cover the country with arcs along the meridians and parallels at intervals of three degrees, and in accordance with this distribution plans were formed for triangulation along the parallels 19° 30', and 28° 30'. Later it was urgently necessary to map some of the states of the nation, such as Yucatan, Chihuahua, Lower California, etc., and it was then necessary to make small geodetic triangulations in each one, and to tie these into the general system by means of chains following the lines of communication or the large rivers, with the exception of the triangulation in Yucatan, which is still unconnected, due to the large extent of mountainous territory which separates that country from the rest of the Republic.

The present state of the geodetic triangulation of Mexico is shown on the attached map (Fig. 1) of the scheme, in which those zones in full black are already finished and those in hatched lines are under way at present.

Instruments and methods of observation

We have divided our triangulation into three orders. The first-order arcs are those for theoretical purposes, or those that serve to form the geodetic net of the country. Second-order arcs are used to cover an area for geographic purposes. And finally, third-order arcs are used to fill in between primary and secondary triangulation to provide immediate control for detailed topographic operations.

Besides the arc along the 98th meridian west of Greenwich, we have an arc of first-order triangulation which runs along the Lerma River, from the valley of Mexico to the port of San Blas on the Pacific Ocean. The field work for this arc is now being done.

We have finished arcs of triangulation for geographic surveys in Yucatan and Aguascalientes, and are now working upon similar arcs in Zacatecas, Sinaloa, Lower California, and Chihuahua.

Triangulation for topographic purposes has been carried on in Veracruz, Alvarado, and Puerto Mexico, for the making of hydrographic charts, and also in Durango and other places for immediate cartographic use.

Whatever the order of the triangulation, the stations are marked permanently on the ground and precise references to them are given.

In this triangulation-work we have used three types of theodolites: That of English manufacture, Troughton and Simms, with graduated circles 30 centimeters in

diameter and equipped with micrometers for angular reading to the nearest second; those of the firm of Repsold und Sohn of Hamburg, Germany, also equipped with micrometers, read to two seconds; and those of the firm of Henry Wild of Heerbrugg, Switzerland, based upon a new optical principle and with which it is possible to make readings to 1/50 of a second. Finally, in topographic triangulation, we have used Zeiss theodolites reading to two seconds. These four types of apparatus may be seen in the accompanying photograph (Fig. 2).

The principal advantage we have gained from modern apparatus, like that of Wild, is the ease of transportation and the reduction of the equipment of an observing-party. These factors have resulted in the reduction of the time necessary for each

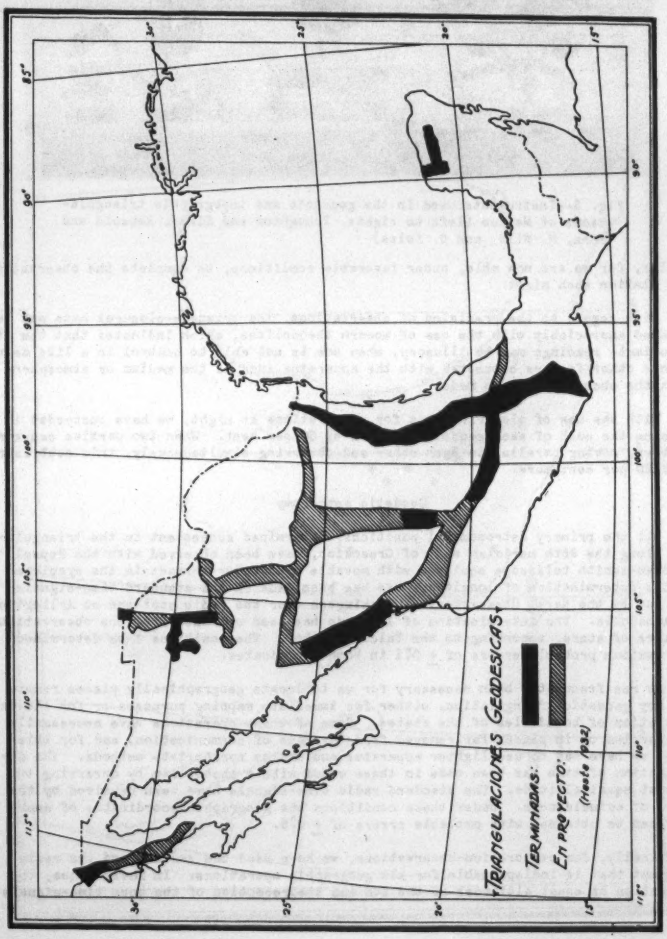

Fig. 1

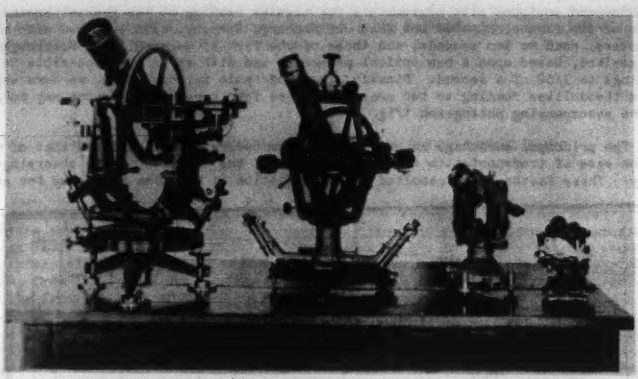

Fig. 2--Instruments used in the geodetic and topographic triangulations of Mexico (left to right: Troughton and Simms, Repsold und Sohn, H. Wild, and C. Zeiss)

station, for we are now able, under favorable conditions, to complete the observations at a station each night.

With regard to the precision of observations, the triangle-closures have not been bettered appreciably with the use of modern theodolites, which indicates that the finer approximate readings may be illusory, when one is not able to control in a like degree various other factors connected with the apparatus such as the medium or atmosphere in which the observations are made.

With the use of electric lamps for observations at night, we have succeeded in reducing the cost of each geodetic station by 60 per cent. When two parties can work together, moving parallel to each other and observing simultaneously, this cost is reduced 20 per cent more.

Geodetic astronomy

All the primary astronomical positions, determined subsequent to the triangulation along the 98th meridian west of Greenwich, have been observed with the Repsold meridian-zenith telescope equipped with movable micrometer-threads in the eyepiece. For the determination of longitude, use has been made of the standard time-signals sent out by the Naval Observatory at Washington over the radio stations at Arlington and Annapolis. The determination of latitude has been obtained from the observation of pairs of stars, according to the Talcott method. The positions thus determined have maximum probable errors of $\pm$ 0".1 in both coordinates.

It has frequently been necessary for us to locate geographically places remote from any geodetic triangulation, either for immediate mapping purposes or for the determination of boundaries of the states. Some of these operations have necessarily been carried on in places far removed from the ways of communication, and for this reason we have had to use lighter apparatus and employ appropriate methods. The determination of time has been made in these cases with a theodolite by observing two stars at equal altitude. The standard radio time-signals have been received by the method of coincidences. Under these conditions the geographic coordinates of each point can be obtained with probable errors of $\pm$ 0".5.

Finally, for exploration-observations, we have used the sextant and the radio equipment that is indispensable for all geographic operations. In these cases, the observation of equal altitudes of the Sun and the reception of the noon time-signals

from the Observatory at Tacubaya give the longitude with a probable error of less than ± 4".0. With similar precision the latitude is obtained by observing the circum-meridian altitudes of the Sun.

Precise leveling

Besides the leveling from the port of Veracruz to Mexico City, with its branch from San Marcos to Tecamachalco, a line of leveling was run from the port of Progreso to the town of Valladolid in the state of Yucatan, a distance of approximately 200 kilometers. This work is based upon the value of mean sea-level determined at the

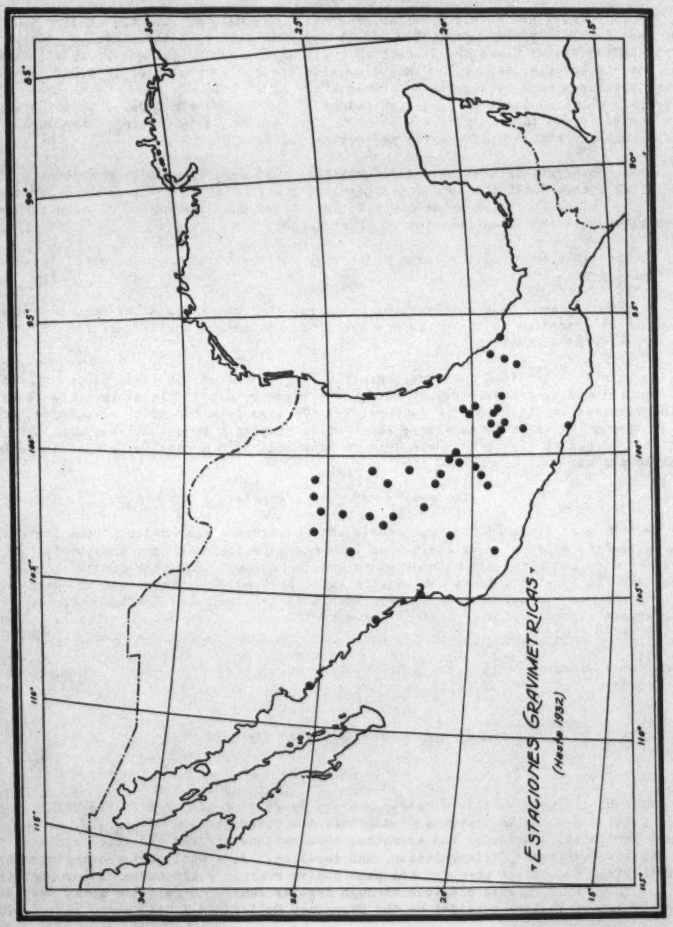

Fig. 3

port of Progreso by a continuous series of tide-observations over a number of years.

This Office now receives data on the tides (datos de mareas) from the principal ports of the country, as permanent representative of the division (Commission) of tides of the International Union of Geodesy and Geophysics. A year ago we installed in the port of Acapulco a tide-gage (mediocariometer) of the Lallemand type with the aim of basing on this datum a future line of precise leveling between the City of Mexico and the said port, and in this manner to have a short line across the Republic from the Gulf to the Pacific.

Gravity-observations

In 1912, a relative determination of gravity was made at our base-station in Tacubaya, D.F., from Washington, D.C. This work was done with the pendulum-equipment of the United States Coast and Geodetic Survey, which was kindly lent by that institution for the purpose, and at the same time with the old equipment of this Office, a German apparatus made by Stuckrath. Immediately after this was done the Mexican government obtained a set of Berger pendulums of the Mendenhall type, with which we have worked in the territory of the Republic from 1925 to date, having determined the values for the intensity of gravity at 43 stations (see Fig. 3).

These observations have been made essentially in accordance with the methods of the United States Coast and Geodetic Survey, with exception of the procedure for time-control by radio, for which we used a procedure based upon the method of coincidences, which eliminates the transportation of chronographs.

The probable error of the value of gravity for the 43 stations observed is about 0.001 of a dyne.

We have reduced these observations and calculated the corrections for topography and isostasy according to the procedure described in the publications of the United States Coast and Geodetic Survey.

We have just obtained from Gaertner in Chicago a new set of invar pendulums, with their corresponding accessories, which we have begun to use in places in which there is no guarantee of steadiness of temperature. We also plan to use this equipment under field-conditions in those places where it is necessary to establish a gravity-station in order to tie it to those observations made with a torsion-balance in geologic explorations.

Topography and photogrammetry

We have just finished the topographic and photogrammetric survey of the State of Aguascalientes, which is completely tied into the geodetic work done previously. Traverses were run along the main highways and local roads, and stereoscopic photographs were taken with a Zeiss camera at a sufficient number of stations to cover the whole territory. In this manner we have been able to obtain the configuration of 5,000 square kilometers, with contour lines at intervals of 50 meters, with less than six months of field work.

Dirección de Estudios Geograficos y Climatologicos,
Tacubaya, D.F., Mexico

PROGRESS OF GEODETIC WORK DURING THE PAST YEAR

C. L. Garner

The geodetic work of this country consists largely of the work of the United States Coast and Geodetic Survey and comprises the determination of gravity, astronomical latitudes, longitudes and azimuths, observations for the variation of latitude, base-measurements, triangulation, and leveling. As a whole the accomplishments for both field and office work for the past twelve months exceed those of any similar period. This has been made possible through regular funds for geodetic work, supplemented by appropriations provided by the Emergency Relief and Construction Act of 1932.

The major activities of the geodetic work of the Coast and Geodetic Survey consist in the extension of arcs of triangulation and lines of levels over the country for the purpose of furnishing fixed positions and elevations, based on a strong national system, for the coordination of hydrographic surveys used in the production of charts and of topographic and other surveys used in mapping.

Formerly the spacing of such control has been at intervals of approximately 50 miles, so that when the net was completed there would be but few points more than 25

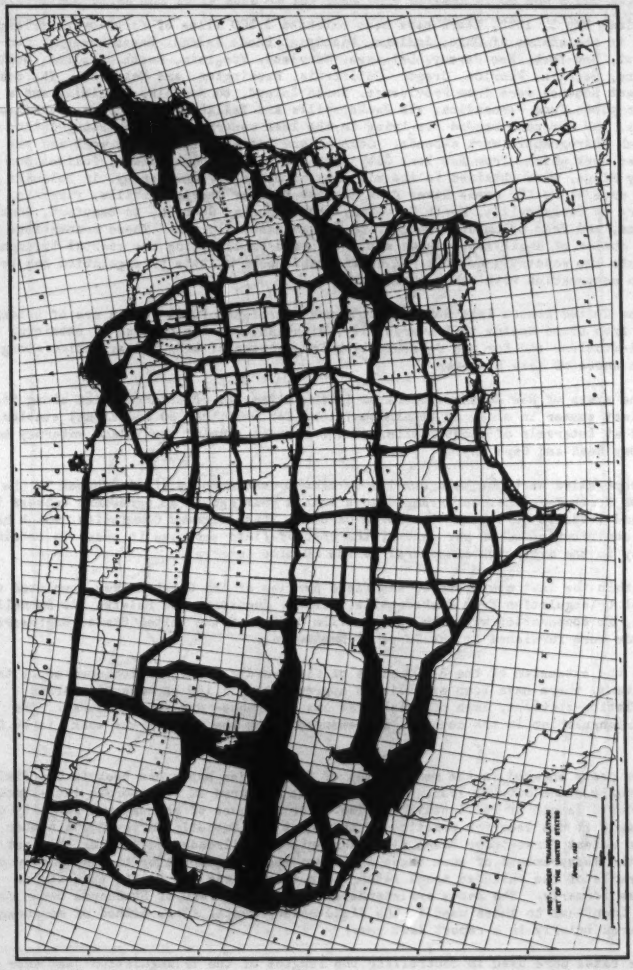

Fig. 1

miles from a triangulation-station or leveling bench-mark.

However, engineers, cognizant of the requirements of the future growth and development of the country, have foreseen the need for a closer spacing of control. This is emphasized by the fact that at its meeting at Yellowstone Park last summer the American Society of Civil Engineers adopted resolutions, addressed to the President of the United States, recommending the adoption of 25-mile spacing for control-surveys in this country.

Since May 1, 1932, there have been extended 3,300 miles of first-order triangulation in the states of Ohio, Indiana, Michigan, Rhode Island, Massachusetts, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, Florida, Oregon, California, Washington, and Nebraska. The most important schemes were from Providence, Rhode Island, to Norfolk, Virginia, and a shorter piece from Fernandina, via Jacksonville and Tallahassee, Florida, to Columbus, Georgia, and are much needed for tying in the less accurate coastal triangulation upon which hydrographic work depends. Connections between the coastal work and the old adjusted work which, from New York City south to Birmingham, Alabama, follows the Allegheny Ridge, were obtained in the vicinity of Barnegat, New Jersey, in Delaware Bay, and by arcs along the James River from Norfolk to near Charlottesville, Virginia, from Mt. Airy to Jacksonville, North Carolina, from Augusta, Georgia, to Beaufort, South Carolina, and from Columbus, Georgia, to Tallahassee, Florida. These connections provide a number of small loops which are being used in adjusting the coastal triangulation into the country's network. A considerable part of this triangulation has been done in cooperation with other organizations.

The United States Lake Survey last summer furnished funds for an arc of triangulation from Grand Rapids to Traverse City, Michigan, for the purpose of obtaining control-stations and for the determination in position of aids to navigation along the eastern shore of Lake Michigan.

The state of New Jersey cooperated in the extension of triangulation along its coast last summer in order to obtain positions for more than 50 additional stations located at intervals of about 2 miles on the oceanic side of the inland waterway between Bay Head and Cape May.

Cooperative work has been carried on almost continuously since October in the state of North Carolina, as arranged more than a year ago by an agreement between the Coast and Geodetic Survey and the North Carolina State Highway Commission, which has made a contribution of 25 per cent of the cost of field expenses in order to obtain priority in the extension of control to the 50-mile interval.

Within the last month one of the field parties of the Coast Survey completed a chain of triangulation from Jacksonville, via St. Augustine and Palatka, to Dunnellon, Florida, in cooperation with the Jacksonville Office of the United States Engineers. The funds were furnished by the Corps of Engineers.

In the extension of the 3,300 miles of first-order triangulation covered by the above items, there have been established approximately 1,150 permanently marked triangulation-stations, each of which also has reference- and azimuth-marks. The total triangulation in the country, as measured along the axes of the work, is 38,000 miles.

The party engaged in the measurement of first-order bases has been in the field continuously since October 1932. This party has measured 22 first-order base-lines, with a total length of 143.5 statute miles. For purposes of economy and facility of measurement it has been the practice of the Coast and Geodetic Survey for a number of years to select first-order bases along tangents of railroads and, during the last two years, the measurements of such bases have been made by supporting the tapes over one of the rails of the railroad track rather than over stakes set to the side of the track, as formerly. The tapes are standardized at the Bureau of Standards under conditions identical to those used in the field-measurements. This method of measurement was covered briefly in a report last year.

The bases were used in controlling the lengths of the triangulation just described, including that portion entering into the coastal arc, and the loop adjustments

tied it in to the old work for which the bases used in deriving the lengths were obtained by very different and much older methods. The fact that the agreements between bases, as carried through the triangulation, were practically the same as for older work is sufficient evidence of the reliability of this new method of measurement.

During the past year there have been approximately 10,200 miles of first-order and about 2,700 miles of second-order levels added to the national net. This brings the total mileage of first- and second-order levels in the United States up to approximately 75,000 miles and it is safe to say that only between 4,000 and 5,000 miles are of second-order accuracy. It should be explained that second-order levels differ from

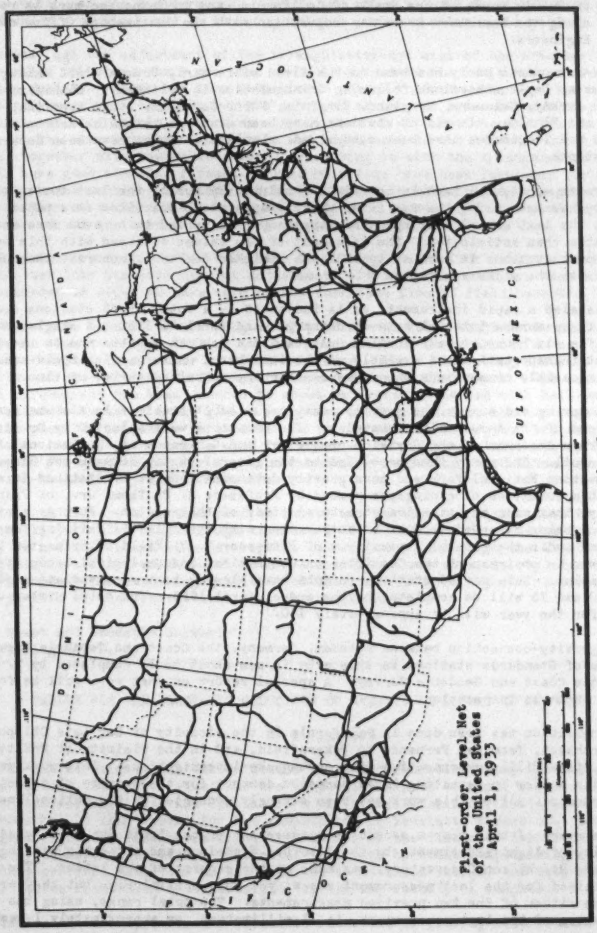

Fig. 2

first-order levels in that the line is run in a single direction without a check except as obtained between bench-marks at the junctions and with work of other organizations. Otherwise all field procedure is the same as for first-order leveling. Leveling in the past year has been extended into nearly every state of the Union. At the present time there are 28 instruments in operation in eleven different field parties which are producing an average of about 2,300 miles of completed first-order leveling or its equivalent each month.

In California and Tennessee some of the leveling has been done in cooperation with local authorities. In California cooperation was with the Division of Highways, Department of Public Works of the State of California, and in Tennessee work is now being extended along the Tennessee River in cooperation with the Chattanooga Office of the Corps of Engineers.

An astronomical party has been in the field since early October 1932 making observations at Laplace stations following triangulation in California, Michigan, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, and Florida. In all 27 stations have been occupied, at which astronomical latitudes and longitudes have been determined. Laplace azimuths have been determined at 32 stations.

A gravity-party has been in the field continuously during the last twelve months. This party has been using the new Brown gravity-apparatus, described in a paper submitted at the last annual meeting. This apparatus has proved to be even more accurate and reliable than anticipated. The agreement of the values obtained with this apparatus at repeat-stations is such as to indicate a higher degree of accuracy than can be obtained with the older apparatus.

It is also a rapid instrument, as is indicated by a total of 63 stations occupied during a three-months interval between January 7 and April 7, 1933. A single pendulum is swung for six hours at each station. A station a day can be obtained on short trips, but transportation and assembly of the instrument under varying field-conditions make it impossible to continue this progress for any sustained period of time.

Last spring and summer the gravity-party occupied 17 stations in Alabama near the southern end of the Appalachian Mountains. The locations were selected by Dr. Arthur Keith, former Chairman of the Division of Geology and Geography of the National Research Council. The party then proceeded to the general region between the Black Hills and Yellowstone National Park and made gravity-determinations at 37 stations in cooperation with a committee of geologists headed by Professor W. T. Thom, Jr., of Princeton University, that made an intensive structural study of that region. Further gravity-work is now being extended in Cuba in cooperation with the Atlantic Refining Company of Cuba and under the general supervision of Professor R. M. Field of Princeton University, who is chairman of the Committee on Geophysical and Geological Study of Oceanic Basins. Data for 63 stations in Cuba have already been received and probably between 70 and 75 will be completed by the end of April 1933. The total number of stations for the year will be approximately 140.

The gravity-connection between Potsdam, Germany, the Coast and Geodetic Survey and the Bureau of Standards stations in this city is now about to be completed by E. J. Brown of the Coast and Geodetic Survey. A special report on that work will be found elsewhere in these Transactions.

Triangulation has been done in California in the vicinity of San Luis Obispo and to the northeast, from San Fernando to Bakersfield, and in the vicinity of McKittrick and Buena Vista Hills in connection with earthquake-investigations. This work was planned with a view to repeating it as occasion demands for the purpose of detecting earth-movements. All of this work has been strongly connected to the national net.

In February of this year a second re-measurement of the Santa Ana Base, used in the velocity-of-light experiments by the late Dr. Michelson and since his passing by Pease of the Mt. Wilson Observatory, was made at the request of the latter. The distances obtained for the last measurement are as yet only preliminary, but they are longer than either of the two previous measurements. The total range, using the preliminary value of the last measurement, is 11 millimeters, or approximately 1 part in

150,000. It is possible that the restandardization of the tapes will reduce these differences. The questions involved are the possible seasonal change of the distance, the effect of tide, etc.

Variation-of-latitude observations were continued throughout the year at Ukiah, California, and Gaithersburg, Maryland. The records of all observations at both stations are sent to Professor Kimura at Mizusawa, Japan, in accordance with the arrangement of several years standing.

The work at the Washington Office consists of the compilation, computation, and interpretation of the field-records. Those and other records furnished from cooperative sources are often used in studying special problems relating to geodesy.

A year ago the adjustment of the triangulation-net east of the 98th meridian had only reached the stage where the most probable values of the latitudes and longitudes with the junction-points had been determined. Since that time the work has been pushed very nearly to completion. The sections of the net between junction-points have been adjusted and in most cases computations of all stations involved have been made. At the same time the computation and adjustment of the Atlantic Coast triangulation, together with the various loops connecting it with the triangulation further inland, have gone steadily forward. Final positions have been furnished for much of the work as far south as Maryland and it is planned to make the adjustments for the loops further south as rapidly as it is possible to do so. Adjusted positions are in great demand and are needed by all organizations basing control on them.

Satisfactory progress has been made in fitting the various sections of the leveling-net into the 1929 General Adjustment, although this work has been considerably retarded in order to take care of the increased flow of field records.

There have been no outstanding developmentsin geodetic instruments during the past year. Small changes looking to the improvement of instruments for use generally have been adopted in a number of different cases. These will add greatly to the facility and ease with which field-parties can carry on their work. One example is that a chronograph has been reduced to about half-size, provided with ball-bearings and a sturdier frame so as to give a much more uniform speed to the instrument than it has been possible to obtain heretofore. A tripod with a larger than ordinary head and adjustable center, which can be used for a number of different instruments, is about to be adopted for general use for such instruments as repeating theodolites, small direction-theodolites, and collimators.

Colored filters have been sent to two of our parties for field-tests to determine their utility in observing through haze and thick atmospheric conditions where visibility is not sufficient with our regular telescopes to bring out the lights and other objects it is desired to point upon. A British survey magazine reported that such filters improve the observing qualities of instruments. The reports received from the field-parties at the present time are not conclusive.

U. S. Coast and Geodetic Survey,
Washington, D. C.

TABLES FOR THE ISOSTATIC REDUCTION OF GRAVITY--A REPORT OF PROGRESS

W. D. Lambert

The tables used by the United States Coast and Geodetic Survey for the calculation of the various isostatic reductions are purposely adapted to rapid computation according to some very definite and special form of the hypothesis of isostasy. It is possible, however, to make tables for the computation of isostatic reductions--tables of a more general nature, adaptable within the limits of the tabulated depths to any form of the hypothesis of isostasy. Tables of this type have the compensating disadvantage that they are more laborious to use than the specialized tables, but they are fundamental tables from which the specialized tables may readily be computed.

Tables of this type for the isostatic reduction of gravity-observations were first published in 1911 by Professor Gino Cassinis, formerly of Pisa, now of Milan.

They were not, however, based on any generally accepted system of zones and compartments and the depths tabulated did not correspond to the ideas now generally accepted as to the actual depth of compensation. Furthermore, they included only the direct effect of topography and isostatic compensation and neglected the indirect effect, or Bowie reduction, due to the warping of the geoid, an effect that it is now deemed desirable to include in the reductions.

For all these reasons it was deemed desirable to compute a new set of tables of the Cassinis type but differing from the Cassinis tables of 1911 in the following particulars:

(1) The use of the Hayford zones and compartments, as recommended by the International Association of Geodesy at the Stockholm meeting of 1930.
(2) The extension of the tables to all depths of compensation from 0 to 125 kilometers.
(3) A smaller tabular interval to facilitate interpolation.
(4) The inclusion of tables for the Bowie, or indirect, effect, again as recommended by the International Association of Geodesy in 1930.

It is hardly necessary to dwell long on the desirability of computing this indirect effect. If we are seeking to determine the figure of the Earth by gravity-methods, all observations must be reduced to one and the same level-surface, usually of course the geoid, and if we apply the direct isostatic reduction, we are dealing with an ideal geoid different from the actual one. The Bowie reduction should be made in order to pass from the actual to the ideal geoid. If, on the other hand, we are merely seeking to account for observed values of gravity, it is obvious that the warping of the geoid may have a considerable effect on those values. Hence again the necessity of allowing for the indirect effect.

As a result of correspondence the work was divided between Italy and this country. Professor Cassinis undertook to compute or to supervise the computation of tables for the direct effect, that should meet the conditions laid down above, and the United States Coast and Geodetic Survey undertook to compute corresponding tables for the indirect, or Bowie, effect. As the zones and ranges of height and depth are the same in both cases and the formulas needed are about equally complex and troublesome, the work is thus about evenly divided between Italy and this country.

A further reason why the Coast and Geodetic Survey undertook the tables for the indirect effect was that it had in hand the reduction of Vening Meinesz's observations of gravity at sea. For this purpose tables were available giving the direct effect according to the special assumptions about isostasy made by Hayford in his gravity-work, but there were no tables for the indirect, or Bowie, effect. The general tables of the fundamental type as described above, quite apart from their general interest and value, were considered to afford the readiest means for computing the necessary specialized tables for the indirect effect based on Hayford's assumptions.

The state of the work is as follows: Cassinis reports that the tables for the direct effect are almost completed and that he expects to finish the work about the end of June, 1933. This country, for various reasons, was late in starting the work. The computations are being made at the temporary field-office in New York in charge of Lieutenant R. L. Pfau. As of April 24, 1933, the work was reported about 10 per cent completed with the expectation that, under favorable conditions, it would be entirely completed by July 1, 1933. Accordingly, at the present moment the work is perhaps 14 or 15 per cent completed.

Completeness, however, does not mean quite so much in the case of the tables computed in New York as in that of the Italian tables. The New York assignment, being intended primarily for the reduction of Vening Meinesz's observations, does not include the smaller depths of compensation, that is, depths below 80 kilometers. The gap, however, will be easy to fill, as so much of the preliminary work has been done and the formulas--there being several of them for use under various circumstances (for example, W. D. Lambert's The reduction of observed values of gravity to sea-level, Bull. Géodésique, No. 26, p. 107, 1930; correspondence between the author and Professor Cassinis has developed other formulas useful under certain circumstances)--are in this interval generally those best adapted to rapid numerical compu-

tation. Even when the assignment of the New York office is completed it will be necessary to make rather extensive interpolations in order to reduce the tabular interval to within convenient bounds.

It is hoped and expected that all these tables with an appropriate explanatory introduction will be published by the Secretary's Office of the International Association of Geodesy. Perhaps the collection will include other tables of interest and value, for the division of work was made rather informally and it is known that scientists of other countries are interested. They have been kept informed of developments and of the progress of the work and it is not unlikely that countries other than Italy and the United States will have tables to contribute to the collection.

U. S. Coast and Geodetic Survey,
Washington, D. C.

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AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

SECTION OF METEOROLOGY

Washington, D. C.
April 27, 1933

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THE AURORAL SPECTRUM AND ITS INTERPRETATION

Lars Vegard

The paper gives a summary of results of investigations carried out in Norway from 1912 up to the present by the writer and collaborators.

Spectrograms from Bossekop 1912-13 showed that the blue and violet part of the auroral spectrum was dominated by the negative nitrogen-bands and that the strong green line had a wave-length considerably greater than assumed at that time.

Measurements carried out at Oslo (1920-21) gave the wave-length of the green line 5577.6 with error less than 7 Å and in good agreement with the nearly simultaneous measurements of Slipher. On the basis of these results Babcock obtained for the green line of the night sky 5577.350.

Spectrographic observations made at Tromsoe (1922-26) gave about 50 lines and bands, most of which were situated in the region 4710 and 3100 Å, where the stronger bands belong to the negative and the second positive group of nitrogen. No hydrogen or helium lines were observed, but a few faint lines were referred to the line-spectrum of nitrogen and perhaps oxygen. Two green lines or bands (5238 and 5139) and red bands referred to the first positive group of nitrogen were observed.

A line near 6300 is remarkable because its enhancement was found to be responsible for the red color of certain aurora. The enhancement of this line appears to be a "universal" phenomenon taking place simultaneously at Oslo and Tromsoe and seems to follow the 11-year sunspot-cycle.

The relative intensity of the most prominent lines and bands within the auroral spectrum was determined and corrected for atmospheric extinction. The auroral spectrum was found to vary with auroral type and with altitude.

Spectrograms were taken of the negative nitrogen auroral bands with large dispersion for temperature-determinations within the auroral region.

Complete account of the results of observations from 1922 to 1926 will be found in a recent paper by the writer (Geofys. Pub., v. 9, No. 11, 1932).

In 1930 the spectral work was combined at the new Auroral Observatory, Tromsoe, built with funds granted by the Rockefeller Foundation, with L. Harang and later also E. Tönsberg as collaborators.

Special attention was paid to the explanation of the long-wave region of the auroral spectrum. From spectra in the infra-red we have as yet measured seven bands belonging to the first positive group of nitrogen. Infra-red bands were recently obtained with a grating-spectrograph giving fairly large dispersion in that region. The nine bands obtained are not yet measured. A considerable number of lines and bands in red were obtained with spectrographs of considerable dispersion. Most red bands belong to the first positive group of nitrogen. Two lines 6302 and 6367 nearly coincide with the OI-lines ($^1D_2 - {}^3P_{1,2}$); but may also be referred to the positive group of N_2 and their origin is still uncertain. Besides the second green line, 5239 and a few other green lines were observed.

In the region of short waves some diffuse bands were observed which coincide with vibrational series typical of solidified nitrogen.

Up to the present 83 lines and bands have been observed, which means that 33 new lines and bands have been detected through the work at the new Auroral Observatory.

The strong green line has been accurately measured with an interferometer. The results, which will be published together with L. Harang, gave values in good agreement with those of Babcock, showing that the green auroral line is identical with that of the night sky. Interferometer-spectrograms corresponding to directions parallel and perpendicular to the ray-streamers were obtained. No Doppler effect was found.

The so-called N_1-line from solid nitrogen as it appears in mixtures with neon was found within the limit of error to coincide with the strong auroral line, and the N_2-, N_3-, N_4-bands of solid nitrogen were found to coincide with other auroral lines or bands.

The accuracy with which the green auroral line fits in with the OI-line ($^1S_0$ - $^1D_2$) is, however, most remarkable. But if this interpretation of McLennan is right we should expect to find in the infra-red and visible part of the auroral spectrum a number of OI-lines, which, however, seem to be absent. If it can be shown that the red lines 6302 and 6367 are identical with oxygen lines ($^1D_2$ - $^3P_{1,2}$) we can no longer doubt that the strong green auroral line originates from oxygen. L. Harang and the writer are trying to measure the two red lines with an interferometer.

If the green auroral line is the OI-line of McLennan, we have to explain why so many oxygen-lines are absent in the auroral spectrum. The writer proposes to explain the predominating intensity of the green line by supposing oxygen to be brought into the OI($^1S_0$)-state through collisions of the second kind with nitrogen in some excited state. The intensity of the green line will then be mainly dependent on the excitation by the electric rays of the predominant atmospheric-component nitrogen. Either nitrogen in the metastable N_2^A-state may act on ozone, or "active nitrogen" may transfer its energy to a normal oxygen molecule and produce dissociation into one normal oxygen-atom and one in the $^1S_0$-state. The energies engaged nearly balance, so the probability of excitation is increased by a kind of "resonance"-effect. The latter alternative is supported by an important experiment of Kaplan showing that the OI-line 5577 can be excited by "active nitrogen."

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THE TRADE-WINDS OF THE EASTERN CARIBBEAN

Oliver L. Fassig

Some of the earliest speculations concerning the general circulation of the atmosphere were associated with a restricted area in the North Atlantic characterized by unusually steady northeast winds. On account of their practical aid in navigation and their striking uniformity in direction and force they became known as "trade-winds" at an early period. Their origin and nature have long been objects of special investigation. Until recent years these winds were known mostly by their variations at sea-level. The rapid development of aerial navigation has directed renewed attention to them in their relations to tropical air-routes, and has made the investigation of conditions to great elevations above sea-level a matter of supreme practical importance.

In July 1920 the United States Weather Bureau established a station at San Juan, Puerto Rico, for upper-air investigations by means of pilot-balloons--a service which has been maintained without interruption to the present time. At first pilot-balloons were released daily only during the hurricane months of June to November. Since 1927 the service has been continuous through the year. The records of these daily cross-sections of the atmosphere to elevations of many thousands of meters, while indicating only direction and force of the winds, furnish a source of material of the greatest importance for a detailed study of the trade-winds, and for the selection of the most efficient air-routes.

The problem for the present is to determine from this rich raw material a degree of definite information concerning the average depth and strength of the trade-winds, with varying conditions of pressure-distribution over the North Atlantic Ocean, to which they owe their origin. Consideration of changes from day to day--a matter of even greater interest and importance to the aerial navigator--will be given only passing notice. The diagrams presented are based upon the reduction of the records of some 2,500 daily cross-sections of the atmosphere at San Juan. The island of Puerto Rico is exceptionally well located for the study of conditions in a typical area of

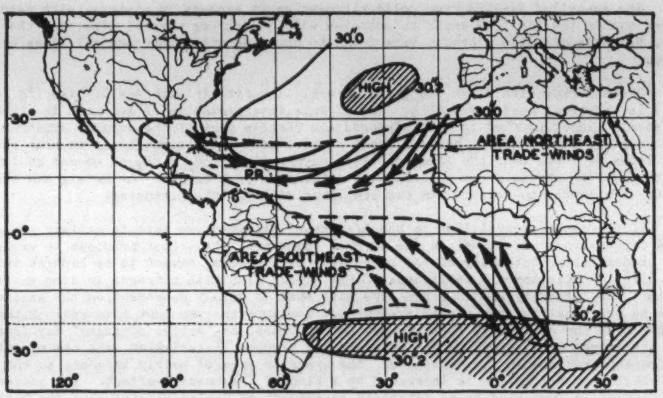


FIG. 1—RELATION PRESSURE-DISTRIBUTION TO DIRECTION AND FORCE OF WINDS, ATLANTIC OCEAN, DURING JULY

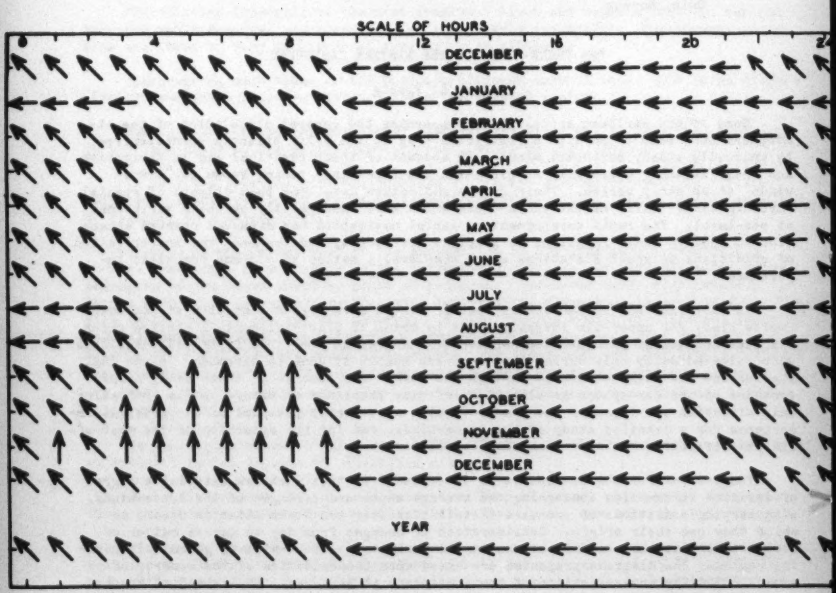


FIG. 2—MEAN HOURLY WIND-DIRECTION AT SAN JUAN, PUERTO RICO, 1900-1929

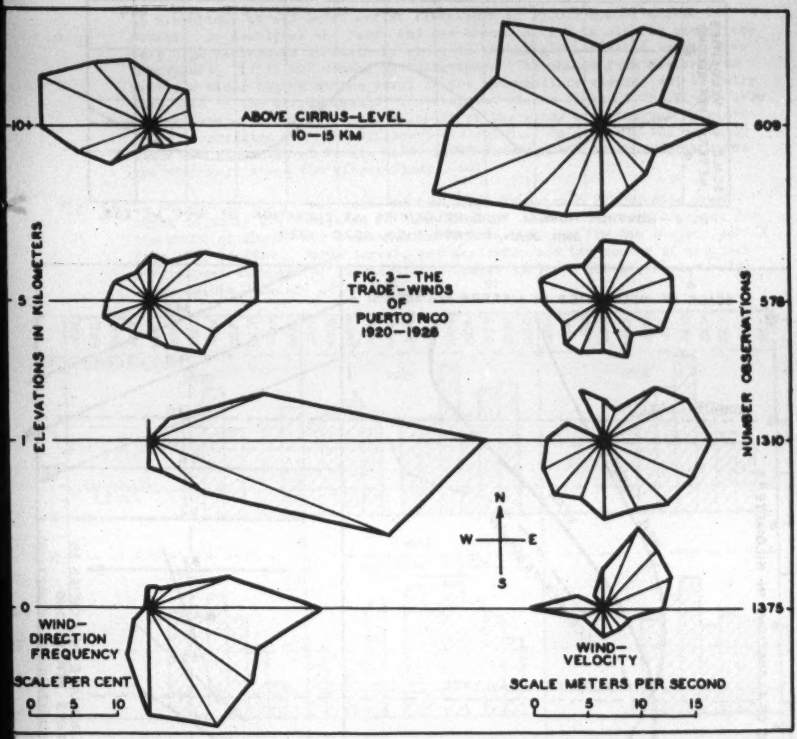


Fig. 1--The pressure-distribution over the Atlantic Ocean controls the direction and force of winds within this area. The normal atmospheric pressure during the month of July, a month of great increase in the strength of the northeast trade-winds, is shown in this Figure. The dotted lines define roughly the areas of the North and South Atlantic dominated by the northeast and southeast trades, respectively.

Fig. 2--The uniformity in the direction of the trades at sea-level is shown in this Figure, which is based upon the hourly records at San Juan for a period of 30 years, from 1900 to 1929. The change from land-breeze to sea-breeze occurs between 9 a.m. and 10 a.m. throughout the greater portion of the year; the reversal takes place between 8 p.m. and 9 p.m. in the fall, and after midnight in the summer months. In January and July the change from sea-breeze to land-breeze is delayed to 4 a.m. and 3 a.m., respectively. The force of the winds is at a minimum of about 6 miles per hour at sunrise, increasing to 16 miles between 3 p.m. and 4 p.m.

Fig. 3--The changes in the strength of the winds at elevations from sea-level to 12 kilometers are shown in this Figure for the year and for the summer and winter months. The winds increase in velocity from sea-level to approximately 1,000 meters, then decrease to the level of the alto-stratus clouds, between 4,000 and 5,000 meters; from this level they again increase to the level of the cirrus clouds, about 10,000 meters.

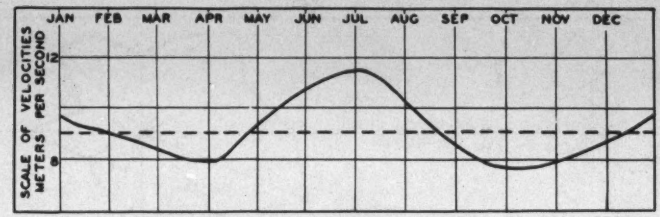


FIG. 4—MONTHLY NORMAL WIND-VELOCITIES AT ELEVATION OF 1000 METERS, SAN JUAN, PUERTO RICO, 1920 - 1929

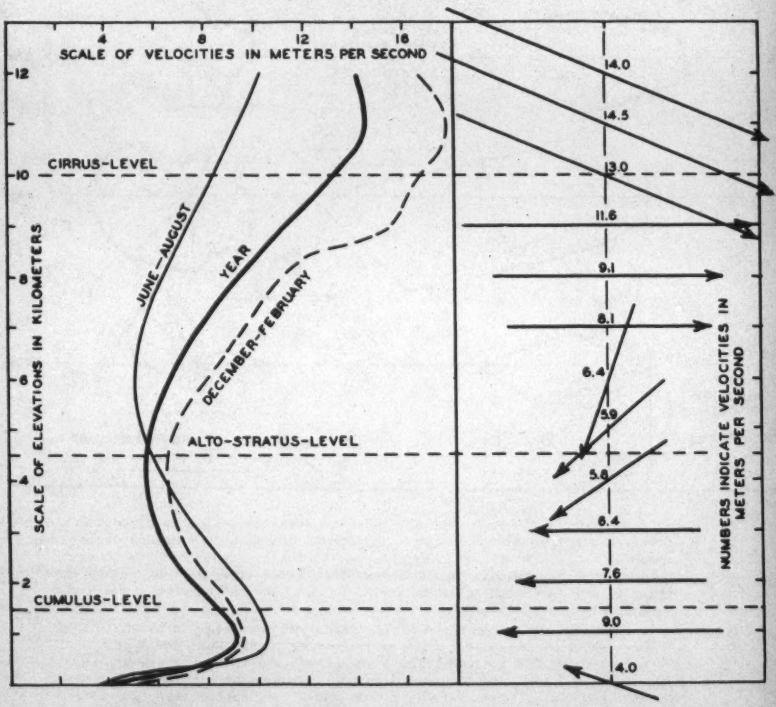


FIG. 5—MEAN WIND-VELOCITIES AND RESULTANT-DIRECTIONS, SAN JUAN, PUERTO RICO, 1920-1929

Fig. 4--The changes in the normal wind-velocity from month to month at an elevation of 1,000 meters are indicated in this Figure. The maximum velocity occurs in July; there is a double minimum, long recognized in surface-winds as associated with periods of light variable winds in April and again in October or early November.

Fig. 5--The prevalence of easterly winds in the trade-wind belt is strikingly shown in this Figure. The diagrams indicate the percentage-frequency of winds for

16 directions at sea-level and at elevations of 1,000, 5,000, and 10,000 meters. At sea-level the land- and sea-breeze effect is clearly shown; the very high percentage of easterly winds is strikingly indicated in the free atmosphere, little influenced by topography. The change from easterly to westerly winds begins at the level of the intermediate clouds, and is fully developed in the cirrus level. The diagrams at the right of the Figure show the comparative changes in the velocity of the winds with increasing elevations, associated with the different directions. In general, the easterly winds are strongest at levels below 5,000 meters while southwesterly winds are strongest above the cirrus-cloud level.

Fig. 6--The changes in the normal depth of the trade-winds over Puerto Rico from month to month are indicated in this diagram. A maximum depth is shown for the month of August and a minimum in the month of May for the 10-year period from 1920 to 1929. July, August, and September are the months of greatest hurricane-frequency for Puerto Rico. Severe cyclonic disturbances rarely occur before June and after October.

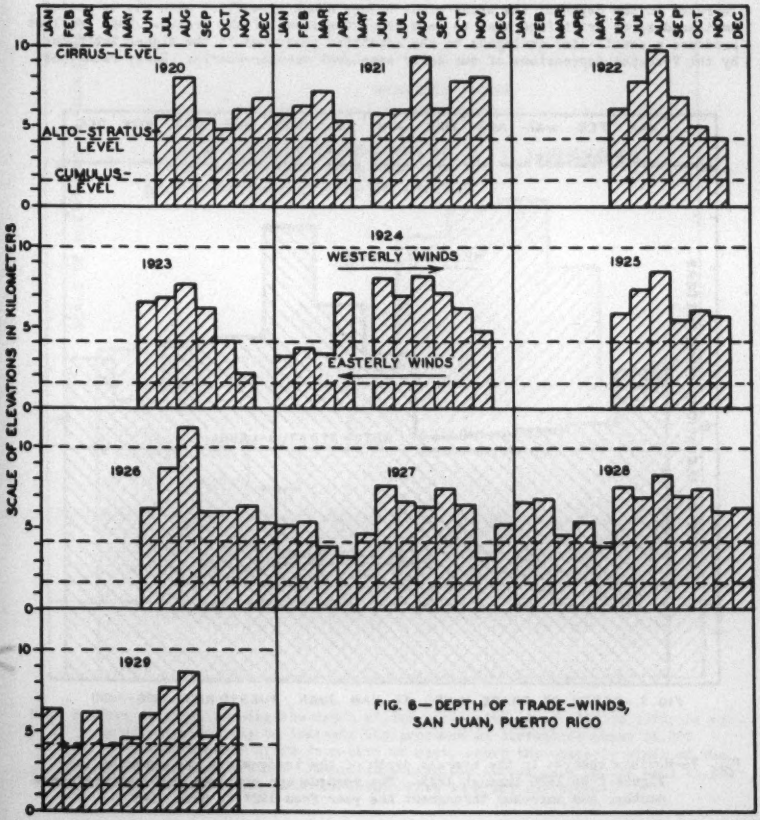


FIG. 6—DEPTH OF TRADE-WINDS, SAN JUAN, PUERTO RICO

the trade-wind belt of the eastern Caribbean Sea. The observations were made by men trained in the art of upper-air investigation, and cover a period of ten years--sufficiently long to yield reliable average values to the level of the cirrus clouds at about 10,000 meters with occasional flights to elevations above 20,000 meters.

The northeast trade-winds of the Atlantic may be regarded as a broad and deep stream blowing out of the North Atlantic area of persistent high pressure; the strength and direction of these winds and the depth of the stream depend upon the development of this area of high pressure and upon the shifting position of its center. The average depth of this broad stream or drift from east to west in the eastern Caribbean varies from less than 4,000 meters in the spring months to 7,000 meters or 8,000 meters in the months of July and August, while the width of the drift is approximately 1,600 kilometers. This great westward-moving stream presents a situation in the tropics analogous to conditions in the higher latitudes generally referred to as the advance of the polar front--though differing in regularity and in the direction of movement. The advance of the polar front from west to east is opposed by counter currents at sea-level; in the trade-wind belt the opposition develops in the intermediate cloud-levels--from 4,000 meters to 5,000 meters above sea-level. Any rapid increase in the depth of the trade-winds brings about a conflict with the so-called anti-trades, or drift from west to east above the level of the trades. This conflict produces a squall-line analogous to the condition presented in the higher latitudes by the V-shaped depressions of our daily sea-level weather-charts. Heavy rains and

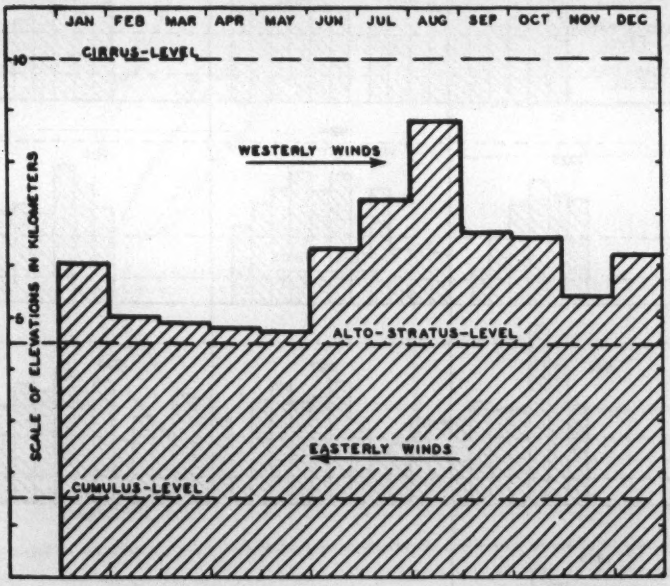


FIG. 7 -DEPTH OF TRADE-WINDS AT SAN JUAN, PUERTO RICO, 1920-1929

Fig. 7--Monthly changes in the average depth of the trade-winds are shown in this Figure from 1920 through 1929. The records are complete for the hurricane-months, and unbroken throughout the year from 1927 to date (1933).

more or less severe atmospheric disturbances are always associated with such conditions, which may be referred to as the trades in flood.

The salient features of the average or normal conditions within the trade-wind belt of the eastern Caribbean area are presented in the accompanying diagrams,

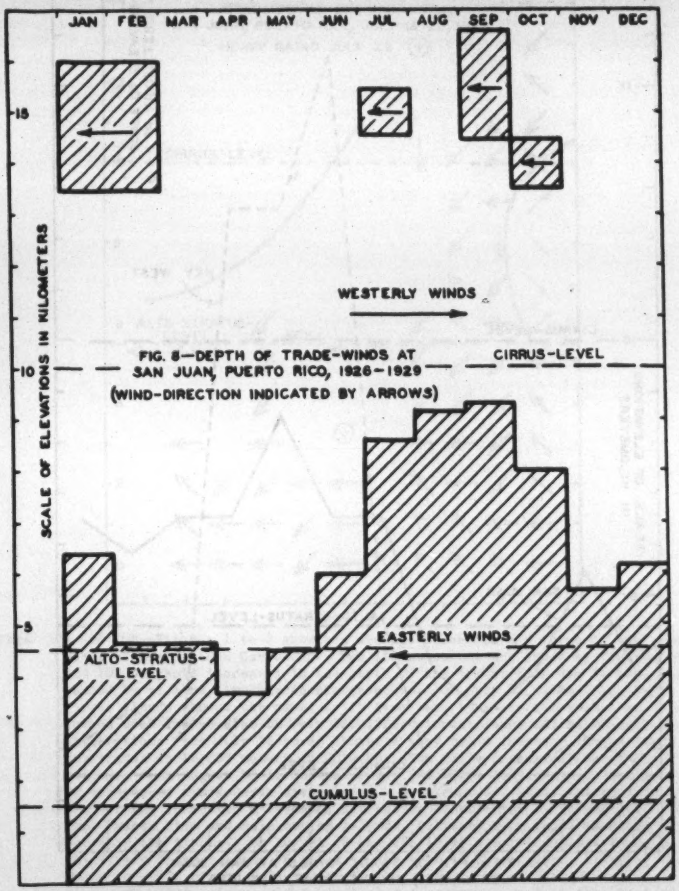


Fig. 8--This diagram, showing the depth of the trade-winds from 1926 to 1929, is reproduced primarily to indicate the presence at elevations above 14,000 meters of another drift from east to west, above the westerly winds of the so-called anti-trades. Favorable conditions during this period made it possible to keep pilot-balloons within view to great elevations.

Figures 1 to 9; Figures 10A and 10B show the rapid changes which may take place from day to day in the direction and in the depth of the trades, and is suggestive of forces tending to explain the cause of our tropical hurricanes.

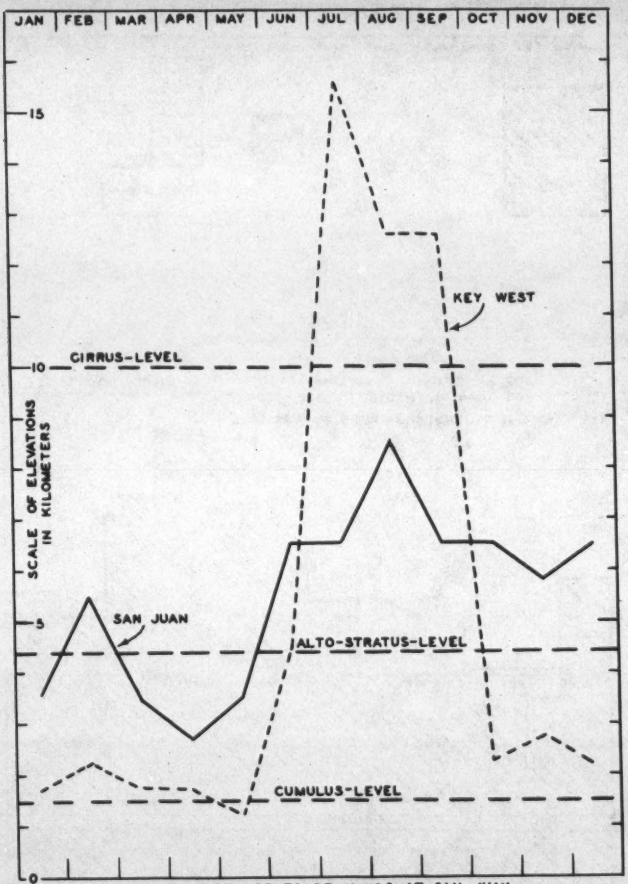
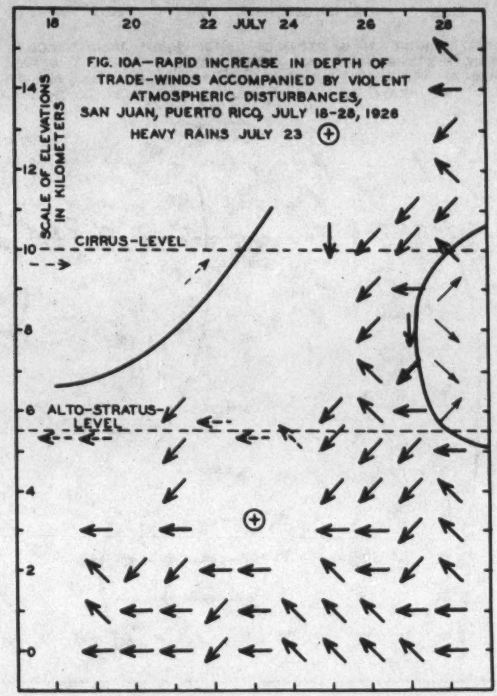


FIG. 9—DEPTH OF TRADE-WINDS AT SAN JUAN, PUERTO RICO, AND KEY WEST, 1920-1925

Fig. 9--From 1920 to date (1933) pilot-balloons were released daily at San Juan, Puerto Rico, and Key West, Florida. This Figure shows the depth of the trades at the eastern end and the western end of the Caribbean area, and reveals a striking contrast in the average depth of 16,000 meters at Key West, compared with a depth of less than 9,000 meters at San Juan, Puerto Rico.



Figs. 10A and 10B--Figures 1 to 9 show the average direction and force of the trade-winds of the eastern Caribbean. Two illustrations are shown by Figures 10A and 10B of rapid increases in the depth of the trades from day to day, accompanied by violent atmospheric disturbances. On July 22, 1926 (Fig. 10A), cirrus clouds showed the usual drift from west to east; torrential rains occurred over Puerto Rico on July 23, 1926; cirrus clouds and pilot-balloon observations from July 25 to 28 showed a very rapid increase in the depth of the trades to 15,000 meters on July 28. The daily cross-section of the atmosphere from August 18 to September 3, 1924 (Fig. 10B), reveals two periods of pronounced atmospheric disturbance. On August 19, 1924, the morning weather-map indicated a V-shaped depression accompanied by torrential rains over Puerto Rico and neighboring islands, followed by a rapid increase in the depth of the trades. On August 28 and 29, 1924, a hurricane was centered over the Virgin Islands about 75 miles to the east of Puerto Rico, bringing the westerly drift of the anti-trades to the surface over Puerto Rico. On August 30, 1924, cirrus clouds indicated a southwest wind at the level of 10,000 meters; on the following days, August 31 and September 1, the winds at the cirrus-level were from the northeast. The records of daily cross-sections of the atmosphere at San Juan abundantly illustrate the close connection between rapid increases in the depth of the trades, or the trades in flood, and hurricanes.

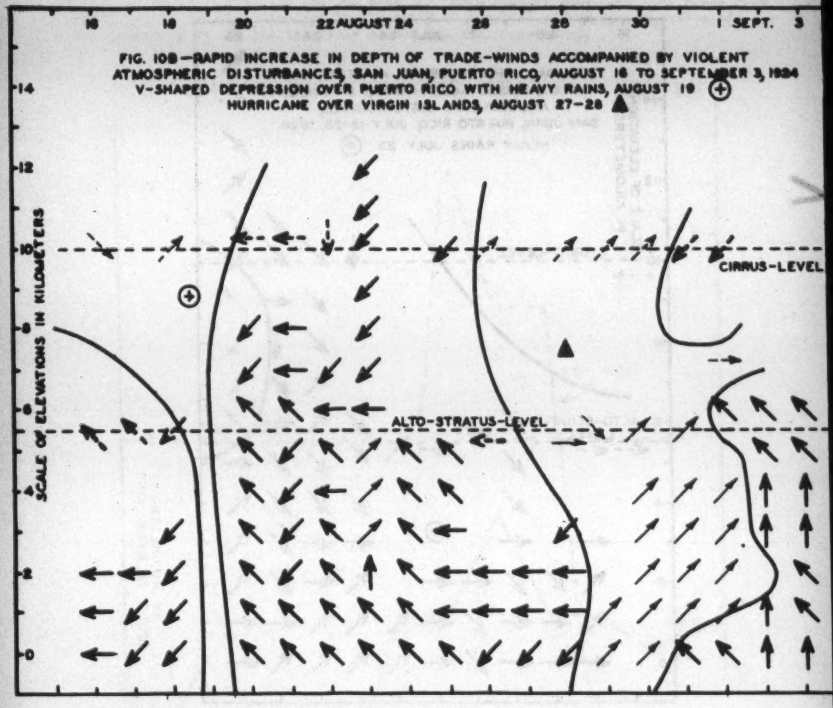


FIG. 108—RAPID INCREASE IN DEPTH OF TRADE-WINDS ACCOMPANIED BY VIOLENT ATMOSPHERIC DISTURBANCES, SAN JUAN, PUERTO RICO, AUGUST 16 TO SEPTEMBER 3, 1924
V-SHAPED DEPRESSION OVER PUERTO RICO WITH HEAVY RAINS, AUGUST 19 ⊕
HURRICANE OVER VIRGIN ISLANDS, AUGUST 27–28 ▲

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SOME METEOROLOGICAL PROBLEMS IN RELATION TO RADIATION

W. J. Humphreys

(a) A possible method of detecting extensive small changes of the temperature of the atmosphere

Whether or not there are fairly regular periods of higher and lower temperatures of the Earth as a whole, and how world temperatures vary, if at all, with the sunspot-period, are questions to which independent investigators have found more or less conflicting answers, owing, of course, to differences in the data examined. Indeed, since these changes at most are very small, it is questionable whether the measurements of atmospheric temperatures, taken near the surface of the Earth, are, or can be, sufficiently free from fluctuations from other causes, such as inversions, supergradients, changes in wind-direction, etc., to settle these points directly. Hence it is suggested that an accurately measurable consequence of temperature-changes, namely, barometric changes at high altitudes, be investigated and that from these findings the temperature-fluctuations be inferred.

To avoid as far as possible fortuitous storm-disturbances, let the stations (the more and more widely distributed the better) be in tropical regions. And in order that the barometric changes may be relatively large, if they occur, let these stations be at as great heights as convenient. Consider, for example, a station four kilometers above sea-level.

A widespread increase in the temperature of the atmosphere by 0.°3 C would put enough additional air above this level, if none flowed off, to increase the reading there of the barometer by about 0.25 mm, while an equal decrease in the temperature would correspondingly lower the barometer. If the flow of the air to or from these low-latitude stations should reduce the fluctuations in pressure to ±0.12 mm, that still would be ten times the tidal effects which have been not only detected but rather closely measured.

It seems, therefore, that this indirect method of following the temperature-fluctuations of the atmosphere as a whole may be worthy of a serious test.

(b) Proposed measurements of radiation in the stratosphere

In 1911, I called attention to evidence that radiation into the stratosphere from beneath varies with latitude, and is least in tropical regions. In 1926, Muge published essentially the same facts and inferences, which subsequently have been used by others. The basic fact is: The temperature of the stratosphere varies with latitude, and is lowest in tropical regions. The inference is: If this temperature is owing essentially to radiation from beneath, then the intensity of this radiation also must vary with latitude and be least near the equator.

Furthermore, in mid-latitude regions, the temperature of the stratosphere is lowest over anticyclones and highest over cyclones. Perhaps this difference in temperature may be owing, in part, to differences in the intensity of the radiation from below.

Direct measurements are needed to test these inferences. They should be made with very accurate instruments from balloons or airplanes in the stratosphere, and of course at night when the moon is below the horizon, so that the measurements may be confined to pure Earth radiation.

It remains, therefore, only to construct suitable apparatus to have another reason--a very real one, too--for making many and extensive visits to the stratosphere, and then the attachment of automatic registering-devices to render further personal trips unnecessary.

U. S. Weather Bureau,
Washington, D. C.

REDUCTION OF METEOROLOGICAL DATA FROM CRUISE VII OF THE CARNEGIE

Katharine B. Clarke

Before the Carnegie set out on her last cruise in May 1928, many of you heard about the program of meteorological observations to be carried out on that cruise. Perhaps you will now be interested to learn what has been done with the data that were obtained and something concerning the publication of the results.

Hourly values of sea-surface temperature, air-temperature, relative humidity, vapor-pressure, and atmospheric pressure were obtained from the recording instruments for approximately 375 days of cruising in the open ocean. These values first had to be corrected for the usual instrumental and observational errors. One rather unusual correction which was made may be of interest. It was found possible to use the temperature-lapse between the deck and cross-trees to correct the mean daytime temperatures recorded in the Stevenson shelter on deck. It is believed that deck-temperatures so corrected more nearly represent the temperatures at the same height over the sea, though they probably are still too high during the daylight hours due to radiations from the deck, sails, etc. (K. B. Clarke, Mon. Weath. Rev., v. 59, 183-185, 1931).

The general scheme of reduction was to collect all the hourly data, except that of atmospheric pressure, into groups of consecutive days during which temperature-conditions were similar. One such group consists of the Gulf Stream crossing; another, a part of the cruise from Callao, Peru, to Tahiti. The air-pressure data were grouped according to zones of latitude. All days when the position of the ship at local mean noon was between 5° north and 5° south were collected, and likewise for latitude-zones of 5° to 15° north, 15° to 25° north, etc. There are 11 such groups of 10° of latitude each. Actually, when it came to studying these data, it was found useful to have some of the air-temperature and vapor-pressure data also summarized according to latitude-zones.

The corrected hourly values for each of the 22 groups of consecutive data and for the 11 groups of atmospheric-pressure data were averaged to give a mean value for each day and a mean for each of the 24 hours. The 24 mean hourly values give the diurnal variations of the elements for the various zones. These were then corrected for non-cyclic change by the usual method.

To facilitate study of diurnal variations of the meteorological elements, the curves representing the mean diurnal variations were treated by harmonic analysis. From these analyses the amplitudes and phases of the 24-hourly, 12-hourly, 8-hourly, and, in the case of the air-pressure, also the 6-hourly oscillations were obtained. A Mader mechanical analyser was used in making these analyses.

The results of these harmonic analyses together with the daily means have provided the data for a study of diurnal and regional relations between air- and sea-temperatures and atmospheric humidity. The harmonic coefficients of the diurnal waves of atmospheric pressure give information for a study of variations of these pressure-waves with latitude and with respect to location at sea or on land. The results of this study are to appear soon in an article in Beitrage für Geophysik.

Equipment was provided on the Carnegie for making observations of evaporation, and in spite of the obvious difficulties of taking such observations on a ship 23 successful runs were made. Most of these were carried through 24 hours and five through 48 hours. The amount of evaporation was to be calculated from the change in salinity of a sample of sea-water between the beginning and end of the run, making due allowances for rainfall. The depth of evaporation in millimeters has been determined by the method used by Wüst in his monograph on Die Verdunstung auf dem Meere (Veröff. Inst. Meeresk., N. F., A, Heft 6, 1920). The values so obtained, of course, do not indicate how much water actually was evaporating at the same time from the surface of the ocean, but thew do give some idea of the amounts of evaporation taking place, and a means of comparing the relative amounts evaporating at different latitudes and under varying conditions.

Aside from these special studies, the final discussion of meteorology on the Carnegie's last cruise will include a running account of weather encountered along the cruise, and descriptions of unusual occurrences such as the typhoon near the coast of Japan.

The pilot-balloon observations have been reduced and studied by A. Thomson. His discussion together with the meteorological and oceanographical results will be published by the Carnegie Institution of Washington in a volume the manuscript for which it is expected will be completed for the printer by December 1933.

Department of Terrestrial Magnetism,
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SOME INTERESTING FEATURES OF OUR WARM AND COLD WAVES

H. C. Willett

The original development of the Bjerknes scheme of the ideal cyclone and of Bergeron's air-mass and frontal concepts was made in the complete absence of direct aerological observations. It represented a remarkably successful attempt to derive

the three-dimensional field of motion of the atmosphere from the careful analysis of surface-reports supplemented by cloud-observations. With the adoption of the Norwegian methods of air-mass and frontal analysis, or modifications of the Norwegian methods, by other European weather-services, and the rapid extension of aerological observations, real progress has been made in the direct observational investigation of air-mass properties and frontal structure. But up to the present hardly a start has been made on the possible utilization of this method of attack on the problems of practical daily weather-forecasting. The one great need at the present time is a better network of aerological observations of greater regularity and extending to greater heights, however such observations can be made. A thorough synoptic analysis based on sufficient aerological material to make possible the determination of (1) the air-mass properties, especially their degree of vertical stability together with their vertical extent, (2) the superposition and the relative movement of air-masses of different types, and (3) the structure and slope of the principal fronts between the air-masses--with such information it should be practicable to make weather-forecasts on a strictly physical basis that will make possible the accurate forecasting of changes which at present can be predicted only after they are already in full progress. We would know then in detail not only the existing field of motion in the atmosphere, but also the amount of the available convective energy and potential energy of mass-distribution, presumably the three principal energy-sources which maintain cyclogenesis. Not only real physical weather-forecasting but the quantitative or mathematical formulation, and solution of most of the problems of dynamic meteorology are waiting on information of this kind. Presumably after a certain amount of experience with an understanding of the development and movement of atmospheric disturbances has been gained, less extensive aerological information in individual situations will be necessary. Probably the next ten years will see more real progress in weather-forecasting than the last forty have seen.

In the last few years in Europe, aerological material has been utilized extensively in the determination of air-mass properties, especially by T. Bergeron and by G. Schinze, and in the investigation of frontal structure, in particular by J. Bjerknes, E. Palmen, and C. K. M. Douglas in England. About two years ago I began a preliminary investigation of the American air-mass properties from the aerological data over a rather restricted period. Eventually I hope, if I can get satisfactory aerological material, to carry out the more difficult investigation of frontal structure and the generation and movement of our cyclonic disturbances.

The two most important American air-masses are the polar continental (typical cold wave) and the tropical maritime (warm Gulf air). A few details which appeared in the study of the properties of these two air-mass types seemed interesting enough in their implications to merit some discussion, although as facts they probably will not be entirely new to any American weather-forecaster.

If the aerological observations at Ellendale are taken as characteristic of the conditions prevailing in the typical severe cold wave in the northwest, the following generalizations may be made about these cold waves:

(1) On the first day of the cold-air outbreak, the winds are likely to be surprisingly uniformly fresh northerly at all levels, the characteristic velocity pertaining to the cold-air outflow being found at the gradient level only a few hundred meters above the ground. On the following days the winds quickly become light at the ground, but diminish in velocity less rapidly aloft.

(2) On the first day of the outbreak a minimum temperature is likely to be found at the top of a turbulence-layer only a few hundred meters deep, above which a small inversion or practical isothermalcy extends for two or three km. On the following day or two the temperature drops at the ground (radistional cooling) and rises at upper levels (subsidence) with the result that a large temperature-inversion becomes established from the ground up to 2- or 2.5-km elevation. At about 4-km elevation is found most frequently the same temperature which prevails at the ground. But it is noteworthy that the warmth produced by subsidence aloft in no way interferes with the attainment of a very low temperature at the ground.

(3) If the relative humidities indicated by the hair-hygrometer at the very low temperatures prevailing in the Pc cold-wave in the northwest are to be accepted, then

at Ellendale in the coldest Pc air-masses the relative humidity is normally high throughout. At the ground it is close to 100 per cent except when the shallow turbulence-layer is present. In this case the humidity is somewhat lower at the ground but increases to near saturation at the top of the turbulence-layer. Consequently in the normal cold-wave temperature-inversion condition, the specific humidity actually increases from the ground up to the top of the main temperature-inversion. This proves conclusively either that the temperature-inversion is not due entirely to subsidence, or that the relative-humidity readings are consistently in error under these conditions.

For the other aerological stations in the middle west the same cold-wave-type conditions prevail as at Ellendale except for some heating of the lower strata of the cold air-mass in the Great Lakes region.

If now we pass to a consideration of the cold waves or Pc outbreaks in the northeastern United States and assume that their characteristic properties are those indicated by the aerological data at Boston, we note the following conditions in contrast to those at Ellendale.

(1) On the first day of the outbreak strong west or northwest winds at the ground which usually increase markedly sometimes with a pronounced shift to the north at upper levels, frequently reach full hurricane-velocity above the 2-km elevation. On the second day the winds may decrease to moderate at the ground, but are likely to retain near-hurricane velocities aloft. In comparison to Ellendale the wind-velocities are greater at all levels throughout the cold-wave period, but the difference is especially marked in the higher levels.

(2) On the first day of the cold wave a temperature at the ground is observed some 15° to 20° C warmer than the corresponding cold-wave temperature at Ellendale. But instead of approximate isothermalcy in the cold air-mass, we find a lapse-rate of about 90 per cent of the dry adiabatic rate in the first km, about 40 per cent in the second, and around 60 per cent through the next 2 km. By the second day of the cold wave we find the surface-temperature normally has decreased slightly, but not as much so as at Ellendale, while a good lapse-rate still persists in the lowest kilometer. Above 1-1/2 or 2 km subsidence usually effects a warming such that the condition tends towards isothermalcy in contrast to the large inversion-effect produced at Ellendale. At the 3-km level cold-wave temperatures average slightly lower at Boston than at Ellendale; at the 4-km level they average 4° C colder, which is quite a significant difference.

(3) At Boston, in contrast to the near saturation found at Ellendale, the relative humidity at the ground averages only slightly over 40 per cent, increasing somewhat with elevation but at no level approaching saturation. The specific humidity falls off continuously with elevation from the ground to the 4-km level, becoming markedly less than at Ellendale at the 3-km level and above. Thus in spite of its relative warmth and consequently greater moisture-content at the ground, the Pc air-mass or cold wave at Boston becomes increasingly colder and drier above the 3-km level than it is at Ellendale in the typical severe cold wave of the northwest.

Probably the following facts contain at least part of the explanation of these radically different cold-wave types.

(1) At Ellendale the cold wave is in the nature of the advance of a cold air-mass moving uniformly at all levels as an entity. Cyclonic circulations and pressure-gradients, at this early stage, have comparatively little to do with the advance--it is more in the nature of an outflow of dense cold air into a warmer region. Hence the uniform movement at all levels. In New England, on the other hand, the cold wave follows usually on the increase to marked intensity of a disturbance which has developed in the Mississippi Valley on the advancing cold front, or as a secondary along the South Atlantic Coast, and which has moved northeastward occluding rapidly. In this process of occlusion and deepening, the maximum intensity of the disturbance is shifted to upper levels. Thus the typical cold-air outflow in New England is dominated almost entirely by a vast cyclonic circulation so that the movement of air at each level depends upon the cyclonic gradient there. This circulation explains the increase of wind-velocity with elevation in the New England cold wave, and perhaps

also the extreme coldness and dryness of the air aloft as the result of very rapid advection from the Arctic. This condition is very similar to that occurring with the principal cold-air flows over northwestern Europe.

(2) Another possible explanation of the extreme coldness and dryness of the Pc air at high levels at Boston compared to Ellendale may be sought in a possible difference between the properties of the cold air-masses in the Hudson Bay region and those of the cold air-masses further west in the same latitude, rather than in a difference in the latitude from which the air is brought. It is quite possible that above 2- or 3-km elevation, over northwestern Canada, the prevailing movement is one of an inflow of relatively warm and moist air from the North Pacific Ocean above the Canadian Rockies. If this is the case, the indicated increase of moisture-content and the initial warmth in the Pc outflows at Ellendale at high levels may be a result of the influence of the warm waters of the North Pacific Ocean. Only aerological soundings in the British Northwest Territory and in the Hudson Bay region can settle this question.

(3) Persistence of the steep lapse-rate throughout the cold wave at Boston in the lower 1,200 or 1,500 meters, with relatively high temperature and low relative humidity at the ground, is doubtless the consequence of the turbulent mixing produced by high wind-velocity and rough terrain to the north and northwest (Appalachian Mountains). The top of the turbulence-layer is marked by a relatively stable layer usually between the 1-1/2- and 2-km levels. The persistence of this turbulence-effect prevents the same degree of radiational cooling at the ground which is found so frequently in the west on the second and third days of the cold wave. But even more important is the effect of this turbulence when subsidence is effecting a rapid heating of the upper-air strata. In the western cold wave the intensification and lowering of the subsidence temperature-inversion does not prevent at all the surface-temperature from falling to very low values, but at Boston as soon as subsidence begins to effect a heating of the cold air-mass below the 2-km level, which occasionally happens within 12 hours of the beginning of the cold wave, the surface-turbulence immediately transmits this heating effect downward to the ground. This effect is occasionally so pronounced that a marked rise in ground-temperatures occurs within 24 hours of the passage of the initial cold front, so that severe cold-wave temperature-forecasts may fail by as much as 15° F, not because of any failure of the expected cold air-movement, but because of failure to make proper allowance for the dynamic and turbulent effects. In one case it was possible to observe within a 7-hour period by three successive aerological ascents in a typical Boston cold wave the appearance above the 4,500-meter level of marked subsidence warming and its downward movement to the 2-km level, with a temperature-increase at higher levels of from 10° to 15° C. All minimum temperature-forecasts for the following night were too low by about 15° F.

Apart from their warmth and moisture in the lowest 2 km, the outstanding characteristic of our T_G (Gulf)air-masses, as indicated by the aerological statistics, is the potential instability inherent in the concentration of water-vapor in their lower strata. The amount of this instability varies considerably from one Gulf air-mass to the next, but the normal conditions are such that in winter an average decrease of the equivalent potential temperature of 10° C in the lowest 2 km is observed. In summer the instability is even more marked in the Gulf air--Groesbeck, Pensacola, and Due West showing an average decrease of the equivalent potential temperature of 20° C in the lowest 3 km. Because of the high relative humidity always found in these air-masses at low levels, comparatively little vertical displacement of the moist air-strata is necessary before this potential convective-energy begins to be effective in producing active convection.

In summer, owing to the absence of any air-masses which are markedly colder than the Gulf air, and hence to a lack of sharply marked warm and cold fronts, there occurs very little frontal forced ascent of the potentially unstable Gulf air-currents. The instability is indicated chiefly by scattered heavy convective thunder-showers, which are local in nature. Also the genesis and maintenance of tropical hurricanes depend entirely on the potential instability of these tropical maritime air-masses.

But it is in the forecasting of the active winter cyclogenesis which so frequently occurs on the front between the Polar and Gulf air-masses in the lower Mississippi valley or along the south Atlantic coast that the potential instability of the warm air is of especial significance. Refsdal was the first of the Norwegian meteorologists to

call attention to the possible importance of the rôle played by conditional instability in the deepening of an occluding disturbance and in the regeneration of an occluded disturbance (Der feuchtlabile Niederschlag, Geofys. Pub., v. 5, No. 12). More recently J. Bjerknes has indicated that conditional instability in the warm air-current tends to favor overrunning of the cold air-mass by the warm, with the establishment of a cyclonic circulation in the overrunning warm current, while stability of the warm current favors a movement more parallel to the Pc cold front with a tendency towards a deflection of the warm current aloft in the warm sector in an anticyclonic sense. (Explorations de quelques perturbations atmospherique, etc., Geofys. Pub., v. 9, No. 9.) In our cases of active Gulf-air cyclogenesis and occlusion by the cold air-mass, the rapid spread of general precipitation with heavy convective rains and frequently thunder-showers behind the cold front indicate clearly both the potential instability of the warm air-current and the cyclonic sense of the circulation in the overrunning warm current. On other occasions the warm air-movement may remain parallel to the Pc cold front for days with little precipitation and no cyclogenesis or air-mass interaction. Presumably the difference is to be explained by the relative stability of the warm air-current in cases of the latter type, though it is very hard to get upper-air data to prove this at just the stations where information is needed; weather-conditions are likely to be so bad that no flight or at best only a very short flight is made. Doubtless also the approximation of the cold-front slope to the equilibrium value must be reckoned with in forecasting air-mass interaction, but this factor may well be of secondary importance in determining active cyclogenesis.

The importance of conditional instability in causing the regeneration of a disturbance on an old occluded front has been definitely indicated in two instances over southern New England during last March. In both cases very weak occluded fronts were advancing slowly towards Boston, one from the north, the other from the west, attended only by some cloudiness and a few scattered traces of precipitation. All weather-forecasts called for continued generally fair weather. In both instances slowly moving disturbances had developed on these fronts within 12 hours; in one case it rained at Boston for 24 hours with a fall of 0.60 inch, in the other case it rained and snowed for three days with a total of two inches of precipitation. The significant feature of these developments, from the point of view of the forecaster, is that the Boston aerological ascents showed on these two mornings as low a temperature at 5 km as had been observed at that station during the entire winter, namely, -37° C in both instances. As the temperature in both cases was a few degrees above freezing at the ground, this meant the existence of a lapse-rate of more than 0.8 of the dry adiabatic rate through at least 5-km elevation, a condition of marked conditional instability.

Many other features of interest concerning our warm and cold waves might be added to those outlined above, but for the present discussion lack of time prevents their consideration.

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THE VALUE OF CLOUD-OBSERVATIONS

Charles F. Brooks

(Abstract)

The value of cloud-observations is internationally recognized by the present second International Cloud Year. The program of this Cloud Year is supplementary to that of the International Polar Year, in that a study of clouds and their motions is valuable for a more complete understanding of atmospheric processes and circulation than is usually possible from balloon- or airplane-observations. The International Cloud Commission has distributed detailed instructions concerning the technique of cloud-observing, emphasizing the care required not only to note accurately the forms of the clouds but also to determine with precision the directions and velocities of cloud-motions at the different levels where clouds may be visible. For cloud-forms, a new international cloud-atlas is provided. This defines more rigorously the different kinds of clouds, such as cirrus, stratocumulus, and provides a convenient code of 27 numbers for summarizing the states of the sky. For cloud-motions, the different types

of nephoscopes are described, as are also apparatus for observing cloud-heights, for, without knowledge of the height of a cloud, the apparent motion cannot be reduced to quantitative terms of wind-velocity.

The very presence of a cloud indicates condensation in the atmosphere. An increasing cloud shows increasing condensation, and a decreasing one, evaporation. Thus the presence or change in the size of a cloud gives at once valuable information as to the trend of atmospheric processes tending either toward rainfall or the reverse. Since a cloud is formed only by condensation of vapor, the presence of a cloud indicates that some cooling process has occurred. Cooling in the free air is most commonly caused by ascent and expansion of air; therefore, the cloud usually indicates ascending air. If the cloud is lumpy (cumuliform) the ascent is localized, as on a warm summer's day; if it is an extended sheet (stratiform) the ascent is general, probably from the sliding of one air-layer over another.

The progressive motion of a cloud tells which way the wind at its level is blowing. Clouds at different levels usually show winds differing in direction and speed. If the lower of two cloud-sheets is moving from the south while the upper is from the north, one may expect an increasing contrast in temperature between the layers, which if carried far will result in instability and probably rain. Furthermore, the speed and direction of movement tell of the pressure-gradients at the heights where the clouds are. These pressure-gradients are determined by the diverse temperatures of the atmosphere over extended areas.

Thus the motions of clouds (as do also the movements of balloons released when clouds are not too low) give valuable information as to the distribution of pressure and therefore of temperature at different levels in the free air. From these some surmises as to the direction and intensity of storm-centers or of areas of high pressure and low temperature can be made even if observations from other points are not available. A valuable adjunct in making such surmises, however, is the sequence of cloud-forms and the development of the density of the clouds. All people are familiar with the usual sequence of light, high, thin clouds to low, thick ones as a storm approaches. There are minor details, however, which the trained cloud-observer notices and interprets in terms of the rapidity of approach and the intensity of the storm as well as of the course the storm-center is likely to take, especially whether the storm will pass south of the station or north of it. The storm passing on the south is likely to bring cool rainy weather, while one passing on the north will usually be attended by generally fair weather and occasional showers at the station.

Besides the value of cloud-observations in the interpretation of atmospheric processes and for weather-forecasting there is, of course, the information useful to aviators, which will enable them to choose the level where the wind will be most helpful in pushing them to their destination.

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THE MOUNT WASHINGTON OBSERVATORY

Robert S. Monahan and Salvatore Pagliuca
(Presented by Charles F. Brooks, Director of the Blue Hill Meteorological Observatory, Harvard University, which is sponsoring the meteorological phase of the project and has provided practically all the meteorological equipment for the three stations.)

Encouraged by the grant of $400 authorized by the New Hampshire Academy of Science, at its last annual meeting, for the study of meteorological conditions and associated phenomena on Mount Washington, those who conceived the project made extensive preparations during the summer and early fall for the reoccupation of the summit during the winter months. Whole-hearted cooperation and sincere interest in the proposal was enjoyed by the Observatory in obtaining building materials, food supplies, and scientific equipment sufficient for the operation of a complete radio-meteorological observatory and for the subsistence of a permanent staff of two observers and a radio operator. The full program of observations began November 18, 1932.

The progress already made and the present status of the project are outlined below. Although the routine observations and special studies already undertaken keep the observers completely occupied on a practically 24-hour schedule, they will be pleased to attempt any cooperative studies suggested by members of the American Geophysical Union.

Personnel--Joseph B. Dodge is director of the project and operator of a radio-relay unit (W1UN) and meteorological comparison-station in Pinkham Notch at the eastern base of the Mountain. He is assisted by Robert S. Monahan, summit observer; Salvatore Pagliuca, summit observer; Alexander A. McKenzie, radio operator of W1PEK, summit station; Charles A. Buckner, operator of meteorological comparison-station at the base-station on the western slope of Mount Washington, and Albert F. Sise, radio-relay operator of Boston traffic.

Preparations--Late September and early October were devoted to transporting up the auto road eight-months' food and fuel supplies, weather-proofing the winter-quarters, and installing the various instruments. The standardization and adaptation of the meteorological equipment to Mount Washington conditions was greatly facilitated by the ten-days' sojourn at the summit of S. P. Fergusson of the United States Weather Bureau and of the Blue Hill Meteorological Observatory of Harvard University.

Quarters--The two-story Stage Office of the Mount Washington Summit Road Company, the only mountain building suitable for such purposes, was loaned to the Expedition for use this winter. The front room of the first floor, 14 by 18 feet, is used as the Observatory proper, and in it are installed the radio equipment, library, atmospheric-pressure instruments, wind-velocity and solar-radiation recorders, plotting-board, writing-benches, files, spare instruments, heating-stove, and the usual paraphernalia expected in such a station.

Also on the first floor are the kitchen and dining-room combined, fitted with sink, oil-stove, coal-stove, water-containers, and numerous shelves for provisions; and the "power-house" in which is mounted the 1-1/2-kilowatt Kohler power-plant, and the current supply of kerosene, wood, and bagged coal.

Overhead are three rooms: One, "Ward 1," in which are placed seven bunks; a second room with considerable storage-space; and the Kaustine toilet. During the early fall the building was completely insulated with eel-grass quilting donated by Samuel Cabot. New floors were laid, storm-windows supplied, wiring installed, and every step taken to insure the efficient transaction of the Observatory business despite the prevailing weather-conditions.

Outside the building have been placed the numerous gas and oil drums contributed by the Colonial-Beacon Oil Company. The garage of the Summit Road Company is used to inflate the pilot-balloons and for storage of the hydrogen tanks and the winter-supply of soft coal and kindling wood.

Communication--Radiophone schedules three times daily are maintained with the Pinkham Notch Camp for the purpose of submitting weather- and climbing-bulletins, news-items, and snow-reports, which are relayed from Pinkham Notch to the Boston station of the Expedition operated by Albert F. Sise. This connection has also proven of great assistance in checking up on mountain-climbers and in the transmission of important mail to the observers.

The New England Telephone Company has connected the private mountain-line, loaned to the Observatory by Henry Teague, to the Whitefield exchange at Fabyans, thus permitting direct communication with the outside. This service has proven completely dependable thus far.

Regular observations--At 7 a.m., noon, and 7 p.m. all the usual meteorological instruments are read and records exchanged by telephone and radiophone with the comparison-stations at the Pinkham Notch Camp and the Base-Station. The early report is immediately transmitted to Boston where the information is made available to the Blue Hill Meteorological Observatory, United States Weather Bureau, and the Meteorological Department of Massachusetts Institute of Technology. This report includes observations on current atmospheric pressure corrected for temperature and altitude;

barometric changes; current, maximum, and minimum temperature; relative humidity; duration, character, and amount of precipitation; amount, kind, and direction of clouds; wind-direction and wind-velocity; and the character of the ground-surface.

At the minimum of three times daily (8 a.m., 2 p.m., and 8 p.m.) another set of readings is made for the International Polar Year Commission. These observations include atmospheric pressure indicated by both mercurial barometer and barograph; psychrometric readings; current and extreme temperatures; wind-direction and wind-velocity; past and current weather-conditions; duration and amount of precipitation; condition of ground-surface including snow-temperature; and visibility-limits. Simultaneous cloud-observations are made in accordance with procedure suggested by the Commission.

These reports are being regularly submitted to the Blue Hill Meteorological Observatory for proper analysis.

The most extreme combination of weather-conditions, recorded up to April 25, occurred at 2 p.m. March 10 when a west-northwest wind-velocity of 145 miles per hour was registered with a temperature of -18°.6 F during a period of 216 hours in which the summit was continuously in fog. (The wind-velocities were obtained with an electrically heated, armless cup-anemometer. The velocities here reported are uncorrected, but comparisons still in progress with anemometers standardized by Professor Shatswell Ober in the Massachusetts Institute of Technology wind-tunnel up to 86 mi/hr seem to indicate that the recorded velocities are somewhat less than the actual ones. Furthermore, it was not practicable to place the heated anemometer on the very summit, which is probably even more windy than the somewhat sheltered Observatory above the roof of which the heated anemometer is exposed. C.F.B.) Another severe combination of wind and temperature developed early in the season on November 26 at 9 p.m. when a northwest wind estimated at 150 miles per hour (using as a comparison the velocity of 132 mi/hr which had been recorded just a week previously) occurred concurrently with a temperature of -21° F.

The minimum temperature of the winter was reached on February 9 at -29° F. The greatest wind-velocity was measured on April 5 between 3 and 4 a.m. at 152 mi/hr. (This is to be compared with a maximum indicated velocity of 186 mi/hr, or about 140 mi/hr true velocity, obtained with a four-cup anemometer on Mount Washington in January 1878. Since the strongest winds are usually attended by rime-forming fog (cloud) on the summit, the highest velocities cannot be recorded without a heated anemometer. Therefore, although the highest record of earlier years seems to have been exceeded three times during the past winter, it is not likely that the highest velocities have been measured yet. C.F.B.)

Wind-measurements have been obtained by means of a heated anemometer of special design with electrically recording device furnished and tested by Blue Hill Meteorological Observatory. A second heated anemometer, with enclosed heating-unit and vacuum-contact mechanism, was built with the aid of the Permanent Science Fund of the American Academy of Arts and Sciences, and installed on the mountain in March.

Special observations--When conditions are suitable the nature of the upper-air currents is studied by releasing pilot-balloons with the complete apparatus necessary for these observations supplied by the Blue Hill Observatory and the United States Weather Bureau. A total of 75 successful day and night balloon-runs have been conducted and hydrogen and balloons are on hand for 150 additional observations. One of the ascensions continued for 63 minutes, on April 19, 1933, when a balloon reached a height of nearly 13.5 km above sea-level.

The peculiar frost-formations, so typical of the highest peaks in the White Mountains, will be an object of particular study, especially during the spring, when the fantastic formation develops rapidly.

The duration and intensity of solar and sky radiation on a horizontal surface is being registered by a pyrheliometer and recorder and the intensity of solar radiation on a normal surface is being observed, all with apparatus loaned by the Eppley Laboratory, Inc., of Newport, Rhode Island. The pyrheliometer, which is continuously exposed, has withstood all the onslaughts of the elements undamaged.

Aided by a theodolite, coast chart, and light-list, the identification of some 15 lighthouses along the Maine, New Hampshire, and Massachusetts coast has been made possible. The two most distant coast lights definitely sighted and identified are those on Monhegan Island, Maine, and Thatcher Island, Massachusetts, at respective distances of 106 and 118 statute miles. The magnesium flares and 400-watt lamp displayed New Year's night were reported from numerous distant points in New Hampshire, Maine, and Vermont. The record report was received from Boothbay Harbor.

A block of wood, infested with satin moths, was exposed to continuous freezing temperature for a period of 3.5 months at the request of the Bureau of Entomology, United States Department of Agriculture. The Observatory has also agreed to gather alpine willow-seeds in the spring and to carry on numerous miscellaneous studies for interested scientists.

Favored by the unique location of the station, considerable research work is being carried on. Heat-conductivity of various types of snow, rime and snow-sediment tests, effect of various types of snow-gage shields on the collection of precipitation, effect of dynamic action of wind on pressure- and temperature-gradients on the west and east slopes of the Mount Washington Range, and size of fog-particles are some of the problems being investigated.

During the summer, S. P. Fergusson of Blue Hill Meteorological Observatory, Harvard University, will make a thorough survey of the temperatures, humidities, and winds around and above the summit, using kites and captive balloons for the purpose. With the Mount Washington Observatory as a base, conditions will be exceptionally favorable for this final test of a series of experiments Mr. Fergusson has been making to determine the nature and extent of the influence of a mountain on the passing air. The results should be of considerable value for the proper interpretation of the observations that have been made on the summit in terms of conditions in the free air at the same level but away from the mountain.

Auroral observations and atmospheric electricity--Thus far the auroras have been singularly deficient. The Observatory is adequately equipped with an auroral atlas, a la Cour star-box, and cameras for classifying, charting, and photographing the Northern Lights whenever they are detected by the hand spectroscope. A few fairly good observations have been made, including descriptions of the phenomena and measurements of arcs and rays with the aid of a theodolite.

There have been at least two remarkable cases of the presence of atmospheric electricity on the wind-vane and on the anemometer guy-wires. The first one showed itself with sparks two inches long in a fairly calm snow-storm, the second one during a heavy wind in the form of a fairly intense discharge-voltage of at least 100 volts.

Radio experiments--Thanks to the great interest of numerous radio manufacturers and supply houses, notably Henry Shaw, chairman of the board of General Radio, the Observatory is equipped with apparatus for transmitting and receiving in the amateur frequency-bands. Considerable experimentation has already been conducted in the 56-megacycle band.

In this connection it has been discovered that reliable two-way communication can be carried on between the summit and Pinkham Notch or Exeter, both points outside the optical path to which transmission on the 56-megacycle band is usually considered to be restricted. Occasionally stations in the Boston area have been able to pick up our voice under certain conditions and more experimenting is being carried on to study the special conditions under which this occurs.

On two occasions extended conversations have been carried on with no difficulty between the summit and the portable outfit operated by Albert F. Sise on Mt. Wachusett at a distance of 130 miles.

Conclusion--The present study could not have been possible without the aid of many interested individuals and organizations. The lifetime of the Observatory is undecided, as the financial resources of the project will be expended by June 16, 1933. An effort will be made, however, to continue at least to the end of the Polar Year.

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THE RECENT THEORY OF GIÃO CONCERNING THE FORMATION OF PRECIPITATION IN RELATION TO THE POLAR-FRONT THEORY

B. Haurwitz

According to the theory of the Norwegian school of meteorologists, the main precipitation of our latitudes is caused by the vertical motions at the surfaces of discontinuity with respect to velocity and density of the air. This conception of important influence which the surfaces of discontinuity have upon our weather is generally accepted in Europe, although sometimes with modifications. It has begun to prove its usefulness in better understanding and forecasting of the weather in this country, mostly through the work done at the Massachusetts Institute of Technology.

Against this theory, well founded by observations and mathematical development, Gião (Essai d'hydrométéorologie quantitative, Beitr. Geophysik, v. 34, 1931) has published another explanation of the system of clouds and of the origin of precipitation connected with the moving cyclones. Since the whole question is of the greatest interest for practical meteorology and for the theoretical understanding of the cyclones, I shall give a short account of Gião's theory and the reasons why it fails.

Gião claims that all condensation-phenomena, during the passage of a cyclone, can be explained mainly by the local pressure-changes and further by the meridional component of the air-motion. In order to prove his opinion he derives the following equation for the change of temperature, dT/dt, of an individual particle of the air

$$\frac{dT}{dt} = -\frac{k^2 g}{rR}\, p^{-1/\gamma} \cot\varphi \int_0^z p^{1/\gamma} v_\varphi dz + k^2 T \frac{\partial \log p}{\partial t}$$

where an irrelevant mistake in calculus, made in Gião's paper, is corrected. In the equation, p is the air-pressure of the particle, z its height, φ is the latitude, v_φ is the latitudinal compount of the wind, $\gamma = C_p/C_v = 1.405$, the ratio of the specific heats, $k^2 = (\gamma - 1)/\gamma$, g is the acceleration of the Earth, R is the gas-constant for air, and r is the radius of the Earth.

Deriving this formula Gião assumed that (1) the changes are adiabatic, (2) the horizontal wind-component is equal to the gradient-wind, and (3) the horizontal differences of the density can be neglected. Small terms of higher order are also suppressed.

We would need too much time to derive his formula here (in spite of the fact that it can be done much more simply than by Gião), but we can easily understand the meaning of the formula. The second term of the right side simply gives the influence of the local pressure-changes, as can be deduced from Poisson's equation. Before we explain the meaning of the first term we must remember that Gião assumed equality of actual and gradient-wind; the relation between the meridional component of the wind and the pressure-gradient therefore becomes

$$v_\varphi = (1/2\Omega \sin\varphi)\ (1/\rho)\ (\partial p/r \cos\varphi\ \partial\lambda)$$

where Ω is the angular velocity of the Earth's rotation $= 7.29 \times 10^{-5}$ sec^{-1}, ρ is density, and λ is longitude. If we assume the pressure-gradient $(\partial p/r \cos\varphi\ \partial\lambda)$ and the density to be constant, we see that v_φ becomes smaller in higher latitudes due to the increasing Coriolis force. Thus for instance if we have northerly winds we must get an ascending motion and cooling of the ascending air-mass, since the inflow through a vertical plane in the east-west direction is greater than the outflow through a plane of the same size farther north. By means of calculation we find for the vertical velocity

$$v_z = (1/\rho)\ (\cot\varphi/r) \int_0^z \rho v_\varphi dz$$

From this Gião concludes that in a northerly current, the air ascends and cools, and in a southerly one, descends and warms. This is the meaning of the first term of the equation for the temperature-change which thus represents the effect of meridional motion upon temperature-changes of the moving air-mass.

Gião claims that these effects of meridional motions and the adiabatic changes of temperature due to the local pressure-changes are the most important causes of the clouds and the precipitation. We will show that these two effects do not give a cooling sufficient for the explanation of the precipitation, which we observe frequently. Let us assume the following example given by Gião for $\varphi = 50°$: Let the local decrease in pressure be -2 mb/hour, a rather high value, $v_g = 10$ meters per second for the lower levels, the pressure at the ground $P_o = 1000$ mb, the temperature at the ground $T_o = 283°$, and $\partial T/\partial z = 0.5°/100$ m. Then we get the following values for A(z), the influence of the local pressure-changes, and for B(z), the influence of the vertical motion of the air-mass caused by the decrease of the gradient-wind blowing northwards.

z in km	0	1	2	3	4	5	6
A(z), °C/hour	0.16	0.18	0.20	0.22	0.25	0.28	0.31
B(z), °C/hour	0.00	0.05	0.10	0.16	0.23	0.30	0.38
dT/dt, °C/hour	0.16	0.23	0.30	0.38	0.48	0.58	0.69
v_z, cm/sec	0.00	0.14	0.28	0.45	0.64	0.84	1.07

From this Gião concludes that for the lower levels of the atmosphere the influence of the local pressure-changes far exceeds the influence of the vertical motions. But it is easy to see that local pressure-changes and a vertical motion caused only by the latitudinal changes of the Coriolis force can not give an explanation of the observed precipitation.

Indeed, if σ is the absolute humidity of the air, then the moisture-content of the whole air-column between z_o and z_1 is

$$\Sigma = \int_{z_o}^{z_1} \sigma dz$$

From the gas-equation we find that

$$\sigma = \varepsilon / R_w T = 0.0027\ \varepsilon / T$$

where R_w is the gas-constant for water-vapor, ε the vapor-pressure (all figures in meter-ton-second units). For ε we assume Hann's formula

$$\varepsilon = \varepsilon_o e^{-z/2170}$$

For T we chose a mean value T_m for the sake of simplicity. Then we find

$$\Sigma = [(4.65/T_m)\varepsilon_o]\ [e^{-z/2170}]_{z_1}^{z_o}$$

We assume as most favorable for Gião's theory that the air is already saturated. Let the temperature at the ground be $T = 283°$, hence $\varepsilon_o = 12.3$ mb; also let the mean temperature of the whole air-column be $T_m = 258°$. (The assumption of saturation in all levels, of a certain mean temperature and of the distribution of the vapor-pressure, can not be fulfilled altogether. But our estimation is not influenced essentially by this inexactness.) We have seen that a pressure-fall of 2 mb/hour causes a fall of temperature of about 0.2°/hour, if the air is not saturated. In the case of saturated air the decrease is much smaller. However, we will apply this value since we want to find an upper limit for the precipitation. That would give a decrease of the saturation-pressure of 0.16 mb, and thus due to the local pressure-changes we find finally a decrease of the water-vapor content of 0.31 kg/m²hour, which represents an amount of precipitation of 0.31 mm/hour. However, it must be kept in mind that this value is probably too high, since our assumptions, namely, dry adiabatic changes and initial saturation, are not true. We have now to estimate the amount of precipitation due to the vertical motion caused by the meridional motions. For this purpose we use the simple formula (for derivation compare f.i.F.M. Exner, Dynam. Meteorologie, 2 Aufl., p. 80 f.)

$$W = \rho v_z (y_o - y_1)$$

in which we put $y_1 = 0$, which can only give an enlargement of the precipitation-intensity. With the same figures as before we get an hourly rainfall of 0.17 mm.

Thus we conclude that, even under assumptions most favorable to Gião's theory, we get a precipitation only of about 0.5 mm/hour, much less than we usually measure. According to Humphreys (Physics of the Air) even a light rain has an average intensity of 1 mm/hour and a moderate one 4 mm/hour. We see, therefore, that Gião's conception of the hydrometeorology is wrong.

It remains only to call attention to the correct theory of the hydrometeors. By means of a more thorough discussion of the calculations reviewed above it can be shown that some of the terms neglected have a far higher order of magnitude than the terms which are taken into account. That follows from an investigation made by Brunt and Douglas (Mem. Roy. Meteor. Soc., v. 3, No. 22, 1928). They got the equations

$$v_x = -(1/2\ \Omega \sin\varphi)\ (1/\rho)\ (\partial p/\partial y) - [1/(2\ \Omega \sin\varphi)^2]\ (1/\rho)\ (\partial \dot{p}/\partial x)$$

$$v_y = (1/2\ \Omega \sin\varphi)\ (1/\rho)\ (\partial p/\partial x) - [1/(2\ \Omega \sin\varphi)^2]\ (1/\rho)\ (\partial \dot{p}/\partial y)$$

where $\dot{p} = (\partial p/\partial t)$, that is, the local change in pressure or the pressure-tendency. These equations represent the well-known gradient wind-relation corrected for the influence of the pressure-change. Differentiating these equations with respect to x and y, respectively, and adding we get for the horizontal divergence of the velocity

$$\partial v_x/\partial x + \partial v_y/\partial y = -[1/(2\ \Omega \sin\varphi)^2]\ (1/\rho)\ [(\partial^2\dot{p}/\partial x^2) + (\partial^2\dot{p}/\partial y^2)]$$

where we assume $\Omega \sin\varphi$ = constant, since we have seen that the effect of the variability of this term upon the divergence and therefore upon the vertical velocity is much too small for the explanation of the amount of precipitation which we usually observe. On the other hand, Douglas and Brunt have shown by means of the preceding equations that the influence of the pressure-changes upon the wind-convergence and therefore the vertical velocity is not to be neglected. By means of this effect we can easily get a convergence of the wind which is sufficient for the origin of vertical velocities of the order of magnitude 10^{-2} m/sec according to Douglas and Brunt. In this manner the observed intensities of precipitation can be explained without difficulty.

Finally it may be remembered that the greatest convergences must occur in the neighborhood of the fronts since here we have the greatest pressure-changes. The physical reason for this is that here the acting forces are greatest due to the sudden changes in air-density and velocity. These forces cause the vertical motion. Gião claims that the Norwegian theory is wrong because the cold air-masses are not obstacles like mountains over which the lighter air-masses ascend. But this is no objection to the polar-front theory since the ascent of the lighter air-masses is caused by the difference of the forces which act upon the two air-masses.

In this review it was only possible to give a very short discussion of the origin of the hydrometeors. But it will be seen from this brief consideration that the Norwegian theory is very much to be preferred to the theory presented by Gião.

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A COMPARISON OF THE LINKE AND ÅNGSTRÖM MEASURES OF ATMOSPHERIC TURBIDITY AND THEIR APPLICATION TO NORTH AMERICAN AIR-MASSES

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Direct solar-radiation, passing through the Earth's atmosphere, is depleted in the following ways: (1) Molecular scattering of the radiation, the theoretical treat-

ment of which by Rayleigh was shown to be in good agreement with Fowle's observations, although there are certain differences, particularly in the short-wave region; (2) absorption by permanent atmospheric gases such as O_3, CO_2, O_2, which will not be considered here; (3) absorption of water-vapor, the amount of which varies exceedingly in the atmosphere; and (4) scattering and absorption by small atmospheric particles such as mineral-dust, water-droplets, salt, etc. Since the depletion of radiation by molecular scattering in a clean, dry atmosphere is known by the work of Rayleigh and Fowle, it is natural to attempt to measure the amount of other optically effective matter in the atmosphere, that is, the atmospheric turbidity, by observing the intensity of the transmitted radiation at the surface of the Earth. Such measures of atmospheric turbidity are important for their bearing on various physical and statistical problems, such as: (1) Determination of variations of the solar constant; (2) variation of the intensity of radiation reaching the Earth; (3) effect of local atmospheric transmission on plant and animal life; (4) determinations of the amount of dust and water-vapor in the atmosphere, which is of importance in explaining and predicting atmospheric condensation; and (5) classification of various synoptic air-masses according to their degree of turbidity.

The problem of defining an adequate expression for the measure of atmospheric turbidity is a difficult one and, as yet, no suitable expression has been found. An adequate measure of turbidity should obey the following requirements: (1) It must be a unique measure, that is, to a given optical state of the atmosphere must correspond a constant measure of turbidity which shall be independent of the Sun's zenith-distance, and thus measurable at any time during the day; (2) the measure must be capable of being split up into its component measures, that is, those of water-vapor and dust; (3) the measure must be capable of being reduced to certain standard conditions for the purpose of comparison with other determinations; (4) the measure must have a distinct physical interpretation; and finally, (5) the measure must be readily and accurately calculable.

The earlier definitions (before 1921) of Marten, $q_4 = \sqrt[4]{I_4/I_o}$, of Dorno, $q_2 = \sqrt{I_4/I_2}$, and of Köhler, $q_{3.86} = \sqrt[3.86]{I_{3.86}/I_o}$, where I_k is the intensity at air-mass k, satisfy only the last two of the conditions.

Linke in 1922 (Transmissionskoefficient und Trübungsfaktor, Beitr. Physik frei. Atmos., v. 10, 91, 1922) made the first attempt to define a turbidity-measure which would obey the first of the above requirements. Starting out with the Bouguer transmission-formula, where I_m is the observed intensity, I_o is the solar constant, and q is the transmission coefficient at m air-masses, Linke assumed that the transmission-coefficient of a wet, dirty atmosphere could be written as

$$q = q_{mol}\,[q_{wet}]^W\,[q_{dust}]^D$$

where q_{mol} is the transmission-coefficient of a clean, dry atmosphere, q_{wet} is the transmission-coefficient of a clean, wet atmosphere containing w cm of precipitable water, and q_{dust} is the transmission-coefficient of a dirty, dry atmosphere of dust-content, D. Linke found some justification in making such an assumption, for, previously, Fowle had observed that for a clean, wet atmosphere the transmission-coefficient at a particular wave-length, λ, could be written as

$$q = q_{mol}\,[q_{wet}]^W$$

Rewriting the Bouguer formula as

$$I_m = I_o e^{-(a_{mol} + wa_{wet} + Da_{dust})\,m}$$

where $a_{mol} = -\log_e q_{mol}$, $a_{wet} = -\log_e q_{wet}$, $a_{dust} = -\log_e q_{dust}$, are the extinction coefficients, Linke computed a_{mol} for m by a rough graphical integration, using the values found by Fowle of the extraterrestrial spectral intensities and of the transmission-coefficients corresponding to various intervals in the spectrum. Although the transmission-coefficients of a wet, clean atmosphere were already known by Fowle's work, accurate measurements of transmission-coefficients of a wet, dirty atmosphere had evidently not been determined. Hence, Linke was dealing with a still unknown quantity,

and so was forced to make not only the above assumption regarding separation of the various extinction-coefficients, but also another equally important assumption. Writing the Bouguer formula as

$$I_m = I_o e^{-[(a_{mol} + wa_{wet} + Da_{dust})/a_{mol}](a_{mol}m)}$$

Linke studied the expression

$$T = 1 + w(a_{wet}/a_{mol}) + D(a_{dust}/a_{mol})$$

and computed tables based on Fowle's measurements, showing almost complete independence of the ratio, (a_{wet}/a_{mol}), on m and w. Hence, for D = 0, T gave a measure of the precipitable water, w, which was independent of m. In order that T have a meaning for $D \neq 0$, Linke assumed (a_{dust}/a_{mol}) to be independent of m and D. Linke calls T the turbidity-factor (Trübungsfaktor), which, if the above assumptions are accepted, gives a measure of atmospheric turbidity, and can be easily calculated from the equation

$$T = (1/a_{mol}m) \log_e(I_o/I_m)$$

Before venturing upon a criticism of the Linke factor, it is first necessary to give an account of the paper of Linke's pupils, Feussner and Dubois (K. Feussner and P. Dubois, Trübungsfaktor, precipitable water, Staub, Beitr. Geophysik, v. 27, 132, 1930), who not only revised Linke's calculations on the basis of more exact measurements of Fowle, but also tried to have the factor obey the second condition above, demanding separation of the water-vapor turbidity from the dust-turbidity, and also the third condition, regarding reduction to a standard level.

Feussner and Dubois utilized the more exact measurements of Abbot and Fowle regarding spectral intensities and transmissibilities, especially those in the ultra-violet and infra-red regions, where values are difficult to measure. When these new measurements were introduced, and a more careful graphical integration performed, the Linke factor, T, was found to be about 30 per cent higher than the old value. Also on the basis of new measurements, the dependence of T on m and w for a clean, wet atmosphere was investigated, and it was found that for a constant w and an increasing m, T first decreased and then increased, the range increasing with increasing w as shown in Table 1.

Table 1

w	m								Authority
	1	2	3	4	6	8	10	15	
cm									
0.5	1.30	1.31	1.34	1.32	1.27	1.26	1.23	1.17	Linke
	1.71	1.64	1.67	1.65	1.64	1.66	1.66	1.72	Feussner and Dubois
1.0	1.69	1.63	1.59	1.56	1.50	1.47	1.45	1.39	Linke
	2.22	2.03	1.98	1.96	1.93	1.94	1.95	2.04	Feussner and Dubois
3.0	2.55	2.34	2.25	2.22	2.21	....	....	....	Linke
	3.33	2.92	2.81	2.77	2.83	....	....	....	Feussner and Dubois

Although Feussner and Dubois put the Linke factor on a sounder basis with regard to water-vapor turbidity, they made no attempt to investigate Linke's two fundamental assumptions regarding the extinction-coefficient of a wet, dirty atmosphere. Furthermore, without justification, they stated that despite the variations in T due to water-vapor alone, "the marked observed correlation (of T) with states and changes of the atmosphere remains essentially unchanged." Until the dust-effect on transmissibility is investigated, this last statement can be nothing more than conjecture.

Feussner and Dubois also discuss the problem of reducing values of T to some standard level for purposes of comparison. This problem had been attacked by Linke and Lauscher previously, but no satisfactory method had been presented.

If two adjacent stations, one higher than the other, measure T at the same time, their values will not be the same for various reasons. First of all, the atmosphere between the two stations will have considerable turbidity, and will render the turbidity-factor at the lower altitude the higher. Then, also, even if the atmosphere between the two stations were clean and dry, the factors would be different due to the molecular scattering in this region and to the influence of pressure on the extinction-coefficients. This leads to an examination of what we mean by an optical air-mass, m. Bemporad found that $m = \sec z$ holds up to $z = 60^\circ$, where z is the zenith-distance, and then a more complicated $f(z)$ thereafter. Now two adjacent stations of different altitude may take observation at same z, but the path in the atmosphere traversed by the radiation in one case will be less than that traversed in the other; thus was introduced the corrected air-mass, $m = (b/b_o)\sec z$, where b is the pressure at the station and b_o is the standard pressure. Hence, to compare T at two stations of different altitude, this correction must be taken into account in the following manner. The Linke factor, T_b, observed at station of pressure b, is given by

$$T_b = [(b/b_o)\sec z]a_{mol}[(b/b_o)\sec z] + (w \sec z)a_{wet}[w, (b/b_o)\sec z]$$

$$+ (D \sec z)a_{dust}[D, (b/b_o)\sec z]\,[(b/b_o)\sec z]a_{mol}[(b/b_o)\sec z]$$

Hence

$$(T_b - 1)a_{mol}[(b/b_o)\sec z] = wa_{wet}[w, (b/b_o)\sec z] + Da_{dust}[D, (b/b_o)\sec z]$$

If now at $b = b_o$, we demand that the turbidity be the same, that is, $w_b = w_{b_o}$ and $D_b = D_{b_o}$, then since $[a_{wet}(b)]$ and $[a_{dust}(b)]$ do not differ much from $[a_{wet}(b_o)]$ and $[a_{dust}(b_o)]$, we can set down for the condition of constant turbidity at b and at b_o the following

$$a_{mol}[(b/b_o)\sec z]\,[T_b - 1] = wa_{wet}[w, (b/b_o)\sec z] + Da_{dust}[D, (b/b_o)\sec z]$$

$$= a_{mol}(\sec z)\,[T_{b_o} - 1]$$

Therefore

$$T_{b_o} = \{a_{mol}[(b/b_o)\sec z]/[a_{mol}(\sec z)]\}\,[T_b - 1] + 1$$

is the corrected turbidity-factor. No attempt has been made to correct T for local conditions such as surface-smoke, etc., for the purposes of air-body classification. To do this the distribution of pollution with height must be known. Hence, for purposes of air-body classification, intensity-observations must be made at stations far removed from local pollution. Linke suggests an absolute minimum of 200 meters for observation concerning air-body classification, but, of course, local conditions must be studied carefully before a site is chosen. On the other hand, observatories must not be too high or they will project above the characteristic turbidities of various air-bodies, and so will not offer a good means of classification according to air-body.

Feussner and Dubois attempted to separate water-vapor turbidity from dust-turbidity by use of filters which would absorb the short-wave radiation (below 600 mμ) and transmit the longer-wave radiation, called respectively the "short"-and "red"-wave radiation. The red radiation is less affected by dust and molecular scattering than is the short radiation, and so Feussner and Dubois claim that the red intensity and its corresponding red turbidity-factor give a good measure of the precipitable water-vapor. Likewise, a good measure of the dust-turbidity can be obtained by observing the short intensities and computing the short turbidity-factor. One great difficulty in the above procedure is to find a filter which will transmit all the solar radiation above 600 mμ and absorb all the radiation below, or even if such an ideal filter cannot be found, to determine the necessary corrections. A good deal of work is being done on filters and it is known that their transmissive powers are far from constant, but vary with temperature, character of radiation, etc. However, even if separation of the red and short radiation were effected then other difficulties would enter, such as corrections for water-vapor absorption in the short-wave region, and corresponding corrections for scattering in the red region.

Because of lack of data concerning dust extinction-coefficients, the actual physical significance of T is uncertain, although for purposes of illustration Linke says that T can be thought of as representing the number of clean, dry atmospheres which would have the same depletionary effect as the single wet, dirty atmosphere. This interpretation of T is not consistent with the definition of T, as Lauscher showed.

Hence, we arrive at the following conclusions regarding T: (1) The independence of T from m is not assured--on the contrary, careful investigations show that even for a clean, wet atmosphere T varies with m, increasingly with increasing w--and, furthermore, assumptions regarding dust extinction-coefficients are still unverified by experiment, and so variation of T with a dirty atmosphere is still unknown; (2) the physical significance of T is not known, and there is no reason to suppose that a physical interpretation will be found when all the necessary experimental work has been done; (3) procedure regarding separation of dust-turbidity and water-vapor turbidity by use of filters is still in need of experimental investigation; (4) progress was made in finding a procedure for the reduction of T to a standard pressure; and (5) T is readily and easily calculable from a simple formula.

Before entering upon a discussion of the Ångström turbidity-measure, it will be interesting perhaps to present statistical data, representing the classification of North American air-masses according to the Linke factor of turbidity. Although, later, I hope to compare the Linke and Ångström measures of turbidity and to indicate which measure in my opinion is the better for certain purposes, I can only state here that for purposes of synoptic air-mass classification, I have selected the Linke factor, not only for reasons which shall be mentioned later, but also because of desire to compare a recent turbidity-classification of European air-masses by Mamontowa and Chromov (L. Mamontowa and S. Chromov, Trübungsfaktor für verschiedene Typen tropospharischer Luftmassen über Moskau, Met. Zs., v. 50, 11, 1933) who used the Linke factor. This investigation was undertaken at the suggestion of B. Haurwitz, to whom also I am grateful for valuable suggestions.

According to the scheme given by Mamontowa and Chromov, I have prepared charts showing the correlation of the Linke factor, T, with the North American air-masses (classified according to the Massachusetts Institute of Technology nomenclature), the characteristic properties of which are soon to appear in a paper by H. C. Willett. I cannot take the time to enter upon a description of the properties and transformations of the synoptic air-masses but will state that: (1) Polar Continental Air (Pc) is air originating over northern Canada and Alaska, and besides being dry and cold, is relatively free from dust; (2) Modified Polar Continental Air (Npc) is air of polar origin which to some extent has lost its original coldness and dryness in the lower layers and has usually already begun to subside, forming the characteristic subsidence-inversions, above which the accumulated pollution and moisture cannot rise; (3) Modified Polar Pacific Air (Npp) is air of polar origin which, having been warmed and moistened in its lower layers by passage over the northern Pacific Ocean, has lost much of its moisture before reaching the eastern United States but has acquired instead dust, smoke, etc.; (4) Tropical Gulf or Atlantic Air (Tg, Ta) is air originating over the Gulf of Mexico or the adjacent portion of the Atlantic Ocean, and is characterized by warmth and high moisture-content; (5) Tropical Continental Air (Tc) is air from the hot, dry southwestern portion of the United States and northern Mexico and has low moisture-content but a high dust-content.

Using the solar intensity-values observed by H. H. Kimball and I. F. Hand at Washington from January to May and from October to December, 1931 and 1932, and by E. M. Harwood, C. F. Brooks, and the author at the Blue Hill Meteorological Observatory from December, 1932, to March, 1933, to compute the Linke turbidity-factors, I classified these factors with the synoptic air-masses, as identified on the Massachusetts Institute of Technology maps. In order to obtain the turbidity-factors characteristic of a synoptic air-mass, it is necessary to use only those intensity-values, observed at times of absence of surface-haze and smoke, and of high clouds in the neighborhood of the Sun. On the basis of very careful notes on sky-conditions taken simultaneously with solar intensity-observations at Blue Hill, values influenced by local conditions mentioned above were discarded. For the Washington observations, however, values could be selected only on the basis of atmospheric conditions at 8 a.m. on days of the observations. This difference in selection at the two stations is shown in the smaller range of synoptic air-mass turbidity-values for Blue Hill.

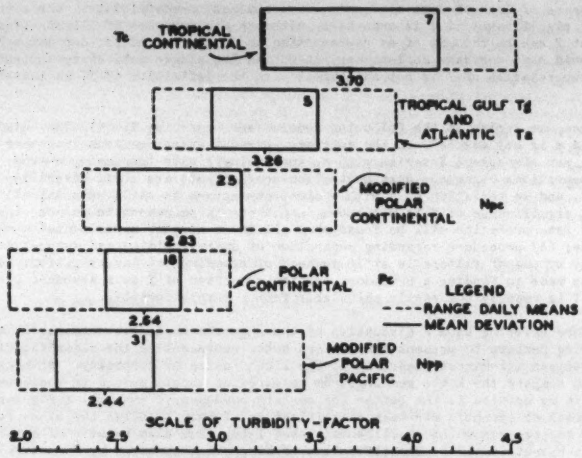

FIG. 1—TURBIDITY-FACTORS, WASHINGTON, JANUARY TO MAY AND OCTOBER TO DECEMBER, 1931-1932

Looking at the distribution of the synoptic air-masses with T for Washington during the autumn, winter, and spring 1931 and 1932 (Fig. 1), we see that the clearest air for Washington is Npp-air, which, on the basis of 31 days of observation, has a mean value of T = 2.44, a mean deviation from 2.19 to 2.69, and a range of daily means from 2.00 to 3.45. The next clearest air is Polar Continental, 18 days, which, although showing certain daily means less than those of Npp, has a higher mean of 2.64, apparently due to the existence of haze- and smoke-layers, caused by subsidence of the air.

The turbidity-factors for 25 days of Npo-air, with a mean of 2.83, are higher still, showing the effect of a steady accumulation of pollution and water-vapor by Npo-air-masses, which have a tendency to stagnate over the southeastern United States during the colder months.

Five days of Tropical Maritime Air show a great increase in turbidity, due to the large moisture-content of the air, while seven days of Tropical Continental Air show

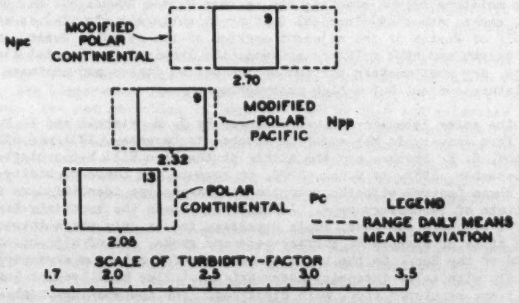

FIG. 2—TURBIDITY-FACTORS, BLUE HILL, DECEMBER, 1932 TO MARCH, 1933

the highest turbidity-values, probably due to the presence of large quantities of dust spread through a considerable height.

The Blue Hill observations (Fig. 2) show that 13 days of Polar Continental Air, with a mean of 2.05, have the smallest turbidity-factors, and that 9 days of Npc-air show a higher mean, 2.32; this reversal of position as compared with the Washington classification may be due to the greater proximity of Blue Hill to the source of the air and to the facts that Pc-air moves more rapidly and over cleaner regions, and has less marked subsidence-inversions than the same air at Washington. Nine days of Npc-air, with a mean of 2.70, show that it has the highest turbidity-factor, thus indicating that only a few days' "aging" of clean, dry Pc-air in the neighborhood of Boston is necessary to increase its turbidity-factor until it becomes higher than that of the Npp-air, which allows its acquired pollution to spread upwards and be carried away by the winds aloft.

The large range of turbidity-values for a single air-mass is due not only to variable local conditions, which cannot be eliminated completely, but also to fundamental differences in the turbidities of one and the same type of synoptic air-mass. These differences in the same air-mass, supposed originally to have the same turbidity, can be accounted for in a number of ways, such as rate of movement, particular path chosen, etc. Then, again, seasonal variations such as snow-cover, lapse-rate of the air-mass, etc., introduce variations in the turbidities of air-masses at their sources and in their wanderings. Later, on the basis of observations from more stations and over a longer period of time, I hope not only to study the influence of such factors as those above on the turbidities of the North American air-masses, but, also, in addition to a classification of synoptic air-masses by maps, will use also upper-air data, plotted on a Rossby diagram (C. G. Rossby, Thermodynamics applied to air-mass analysis, Mass. Inst. Tech. Met. Papers, v. 1, No. 3, 1932), which offers a more accurate identification of air-masses, and also indicates clearly variations in thermal and moisture-properties of air-masses originating at identical sources.

Ångström defines a dust turbidity-measure (A. Ångström, Atmospheric transmission of Sun radiation and dust in the air, Geog. Ann., v. 11, 156, 1929; and Atmospheric transmission of Sun radiation, II, Idem, v. 12, 130, 1930) by assuming that the water-vapor absorption could be measured by Fowle's empirical formula

$$F \text{ (in gm-cal/min-cm}^2\text{)} = - 0.10 + 0.0064\ e_o\ m$$

where e_o is the water-vapor pressure in mm at the station, and m is the optical air-mass.

Starting with the formula verified by Fowle,

$$I_\lambda = I_{o\lambda} e^{-(a_1 + a_2)m}$$

where a_1 is the molecular extinction-coefficient and a_2 is the dust extinction-coefficient, Ångström shows that on the basis of Lundholm's experiments with MgO, SbO, ZnO particles, a_2 could be written in the form

$$a_2 = \beta/\lambda^\alpha$$

where α and β are independent of λ, and where $0<\alpha<4$. For particles of diameters from 0.25 to 2.0μ, Lundholm found that α varied from 3.6 to 0.7, that is, was a decreasing function of the diameter. From observations collected from widely scattered stations at different altitudes throughout a number of years, α and β were computed by observing intensities at different wave-lengths and assuming the Rayleigh coefficient for molecular scattering to hold true, and α was found to have values between 1.0 and 1.5 which corresponded to optically effective particles of diameter about 1.0μ. Under abnormal conditions such as volcanic outbreaks, α was found to decrease to 0.5 and less, thus indicating that the average size of the optically interfering particles was increased by the introduction of volcanic dust. Ångström's determinations indicate that the 1.0μ particles dominate, optically speaking, over a long period of time. He calls α the "size-exponent" and β the "turbidity-coefficient," "which, for constant α, must be expected to be proportional to the amount of dust in the air."

On the basis of the preceding work Ångström shows how to find β corresponding to a particular optical state of the atmosphere, by observing the entire solar intensity, I_m, and e_o, and making use of curves relating the values of $(I_m + F)$ with m, where

$$I_m + F = \int_{\lambda=0}^{\lambda=\infty} I_o \, q^m \, e^{-\beta/\lambda^\alpha} \, d\lambda$$

and α is taken as 1.3, and q is the Rayleigh transmission-coefficient.

The reduction of β to a standard level may be performed by means of the following empirical formula, which Ångström derived from smoothed values of Kimball's dust-data,

$$\beta_h = \beta_o \, e^{-\delta h}$$

where $\delta = 0.69 \times 10^{-5}$, and h is the height in cm.

Ångström also shows how by use of filters which transmit about 90 per cent of the radiation above 600 mμ. β may be determined independently of the empirical formula of Fowle. If the transmission-coefficient of the filter is γ, then the observed red intensity is

$$I_{red} = \gamma \int_{0.6\mu}^{\infty} I_{o\lambda} \, q^m \, e^{-(\beta/\gamma)^\alpha m} \, d\lambda - \gamma F$$

Dividing by γ and subtracting from

$$I_m = \int_o^\infty I_{o\lambda} \, q^m \, e^{-(\beta/\lambda^\alpha)m} \, d\lambda - F$$

we get

$$I_m - (1/\gamma) I_{red} = \int_o^{0.6\mu} I_{o\lambda} \, q^m \, e^{-(\beta/\lambda^\alpha)m} \, d\lambda$$

Hence, if I_m, I_{red} are observed at a particular m, then β may be determined from curves giving the values of $[I_m - (1/\gamma)I_{red}]$, F being eliminated. Once β is determined, then $(I_m + F)$ may be found from the first set of curves, and so F, the water-vapor absorption, may be found.

It can be easily shown that if β is proportional to the amount of dust in a vertical column then it is independent of m. I shall not take the time to prove this but shall enter immediately into a more serious topic, that of constancy of α. Although Ångström gives a formula for the reduction of β to a standard level, yet, as Linke and v. dem Borne (F. Linke and H. v. dem Borne, Die Wellenlängenabhangigkeit der Strahlungsextinktion trübender Teilchen, Beitr. Geophysik, v. 37, 41, 1932) point out, serious errors enter in Ångström's use of optical air-mass, m, in its geometrical sense only, that is, making no correction for altitude, and also in the Ångström use of the uncorrected Rayleigh transmission-coefficients. When these corrections are applied, Linke and v. dem Borne show that the fundamental assertion of Ångström regarding constancy of α for different altitudes, location, and season are incorrect as Table 2 indicates.

Table 2

Station	Height	After Ångström		After Linke and v.d.Borne	
		α	β	α	β
	m				
Washington, D. C.	35	1.24	0.098	1.20	0.087
Upsala, Sweden	35	(0.70)	(0.90)	1.15	0.055 (April)
				0.91	0.130 (July)
Bassour, Algeria	1160	1.22	0.031	2.09	0.018
Hump Mt., Calif.	1500	1.33	0.031	1.32	0.025
Mt. Wilson, Calif.	1780	1.26	0.018	1.62	0.012
Calama, Chile	2250	1.37	0.023	1.43	0.056

The corrected values of α show how α varies with height, location, and season, and, so, accordingly render values of β, which depend on α, unsuitable for purposes of comparison. This objection, however, vanishes if we assume on the basis of Ångström's experiments that the dust extinction-coefficient for various optically effective sizes, that is, for various α, can be written in the form

$$s_2 = \Sigma_\alpha (\beta_\alpha/\lambda_\alpha), \quad 0<\alpha<4$$

If, now, we depart from the Ångström assertion that the values of β_α for $\alpha \neq 1.3$ (about) are small compared with $\beta_{1.3}$ (corresponding to optically effective particles of size about 1.0μ), and so all terms except the $\alpha = 1.3$-term may be neglected, the extinction-equation now assumes the form

$$I_\lambda = I_{o\lambda}\, q^m\, e^{-\Sigma_\alpha(\beta_\alpha/\lambda_\alpha)m}, \quad 0<\alpha<4$$

Hence, if experimentally the values of α are determined for various kinds of atmospheric particles (as Linke and v. dem Borne do for several species), and the values for n types prevalent in the atmosphere are found to be, $\alpha_1, \alpha_2, \ldots, \alpha_n$, then the various values of β which are proportional to the amounts of α_1-particles present may be found by observing I_λ in n spectral regions, where absorption by water-vapor and other gases is small, and then solving the system of n linear equations for the n unknown values of β

$$\beta_1/\lambda_1^{\alpha_1} + \beta_2/\lambda_1^{\alpha_2} + \ldots \beta_n/\lambda_1^{\alpha_n} = \log_e q(I_{o\lambda_1}/I_{\lambda_1})^{1/m}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\beta_1/\lambda_n^{\alpha_1} + \beta_2/\lambda_n^{\alpha_2} + \ldots \beta_n/\lambda_n^{\alpha_n} = \log_e q(I_{o\lambda_n}/I_{\lambda_n})^{1/m}$$

where the values of m and of q need not necessarily be constant at the measurements of the various values of I_λ.

Hence, a sequence of turbidity-coefficients may be determined which are proportional to the amounts of optically effective dust of sizes corresponding to the various values of α. The separation of optically interfering dust according to size has important bearing on certain meteorological problems, such as the growth of water-particles due to condensation of water on hygroscopic nuclei, and also the tracing of dust-clouds, of different origin and characteristically different dominating optically effective sizes, throughout their course of travel--for example, clouds of salt-particles, which play such an important rôle in atmospheric condensation-processes.

The method briefly suggested above requires for the determinations of the various values of α and of β, selective radiational intensities, measuring instruments, such as the Smithsonian spectrobolometer and various types of alkali photoelectric cells (A. L. Hughes and L. A. DuBridge, Photoelectric phenomena, chap. 5, McGraw-Hill, N.Y., 1932); the latter type of instrument is not nearly so expensive as the former, and at present a great deal of work is being done by physicists investigating the extraordinary selective powers of certain types of alkali cells, such as the cuprous oxide, the potassium, and the caesium.

A final word concerning the relative values of the Linke and Ångström measures. It is my opinion that, even if the necessary experimental work were to be performed on the Linke factor, the factor has about reached its limits of usefulness. It will continue to serve as a certain "measure" of atmospheric turbidity, the nature of which will probably never be fully understood, and as a classification of the optical properties of various synoptic air-masses, but for finer selective measurements, such as the separation of dust-particles of different optical sizes, the Ångström coefficients will probably be emphasized in the future along the extension suggested above.

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Cambridge, Massachusetts

A STUDY OF THE TIME-, AREAL-, AND TYPE-DISTRIBUTION OF TORNADOES IN THE UNITED STATES

Charles Wilson Brown

In taking up the study of tornado-occurrences in the United States, we have found that hitherto they have been studied chiefly from the standpoint of geographical distribution by states, and possibly their subdivisions. The frequency of the occurrence of weather phenomena has been used as a basis for the calculation of the premium rate on weather insurance. No attention has been paid to the type of the tornado with reference to special meteorological conditions under which it developed. Furthermore, the seasonal distribution of the tornadoes has not been considered. The fact that tornadoes may occur more frequently at one time of the year than another has been lost sight of. Again the time-place data of occurrence, in which certain tornadoes occur in a definite region at certain periods of the year, up to the present time has not been studied, and the triple combination of time-place-type tornado-data, up to the present study, has not been correlated.

The aim of the present statistical study, which has been carried out in a most painstaking and indefatigable manner by W. O. J. Roberts under my supervision, has included some 5,000 tornadoes as recorded in the publications of the United States Weather Bureau. Each tornado has been recorded on cards and filed in different ways. It might be said that this present paper is but a report of progress, for it includes the detailed study of only 2,017 tornadoes occurring from 1917 to 1931. Moreover, in order to classify as to type, each and every occurrence has been studied with reference to the weather-map of that date, the preceding, and the succeeding day, to determine whether or not the tornado was associated with a well-developed cyclonic low-pressure area (cyclonic) or whether such a cyclone was weak or lacking (convective). If the cyclonic control seemed to be feeble or wanting and temperature-developments indicated the existence of an unstable atmospheric condition, the term convective was applied. Such was the basis for the division of the tornado-type.

The yearly distribution of nearly 5,000 tornadoes from 1880 to 1931, however, is shown in Figure 1. It is hard indeed to account for the erratic nature of this curve. The big trough from the year 1900 to 1907 apparently cannot be assigned to the human factor. It is difficult to conceive of a seven-year period in which so few tornadoes occurred or so many failed to be recorded. One might imagine that the peak of 1929-30 is more pronounced than that of 1885 because of the increased density of population in the eastern fringe of the high plains and of better methods of communication and press reporting. The curve leading symmetrically downward to the trough of 1900 to 1906 and upward again is interrupted by only one low spot on either slope in 1889 and in 1914-15 The figures for 1932 and 1933 will probably determine to a certain extent the nature of the other slope of the last peak. No attempt has been made to correlate this curve with temperature, rainfall, solar radiation, sunspots, or other established curves. That will be a part of the future study of the general problem.

The distribution-maps of the two types give the general distribution of tornadoes over the period of the last 15 years (Figs. 2 and 3). These tornado-tracks have been plotted by utilizing a large county map of an atlas and drawing the track through the towns mentioned in the report. The tracks confirm the common knowledge that the tornadoes move a little north of east. The tracks of the colder cyclonic season seem to show a wider divergence in direction than the tracks of the tornadoes of the heated season, or of the convective type. As a general rule, the cyclonic tornado-tracks are longer than in the case of the convective tornadoes. Again, certain states have relatively few tornadoes during the heated season, but some states show many tornadoes that develop under the influence of cyclonic low-pressure areas, especially where a well-marked wind-shift axis exists in a lobate low.

It is true that certain areas are common to both, as will be brought out later, but in general the distribution of the convectional tornadoes ranges from northern Texas northeasterly through Kansas and Iowa to Wisconsin. Some of these areas are frequented by cyclonic tornadoes, but for the most part the latter type occurs in three or four zones, roughly north-south in direction, that radiate from the Gulf states. The first and most westerly, made up of shorter tracks, in general extends northerly from the southern Texas coast-line through the eastern portion of that

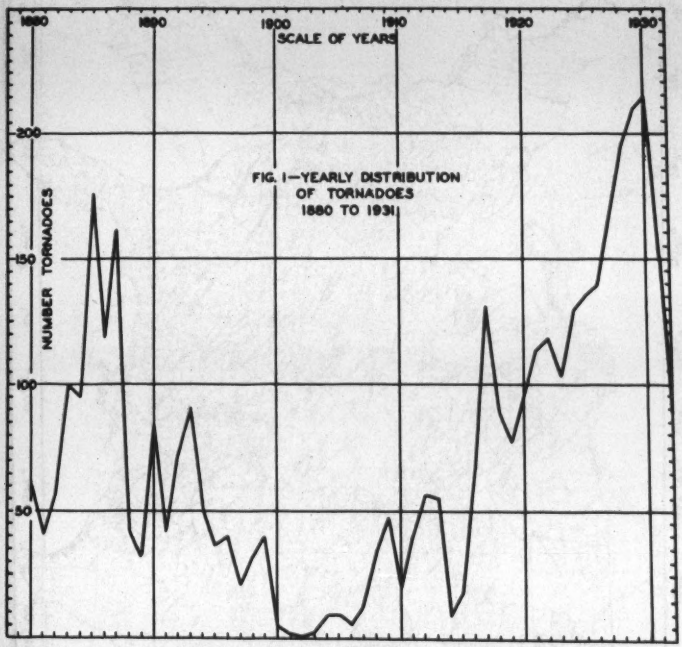


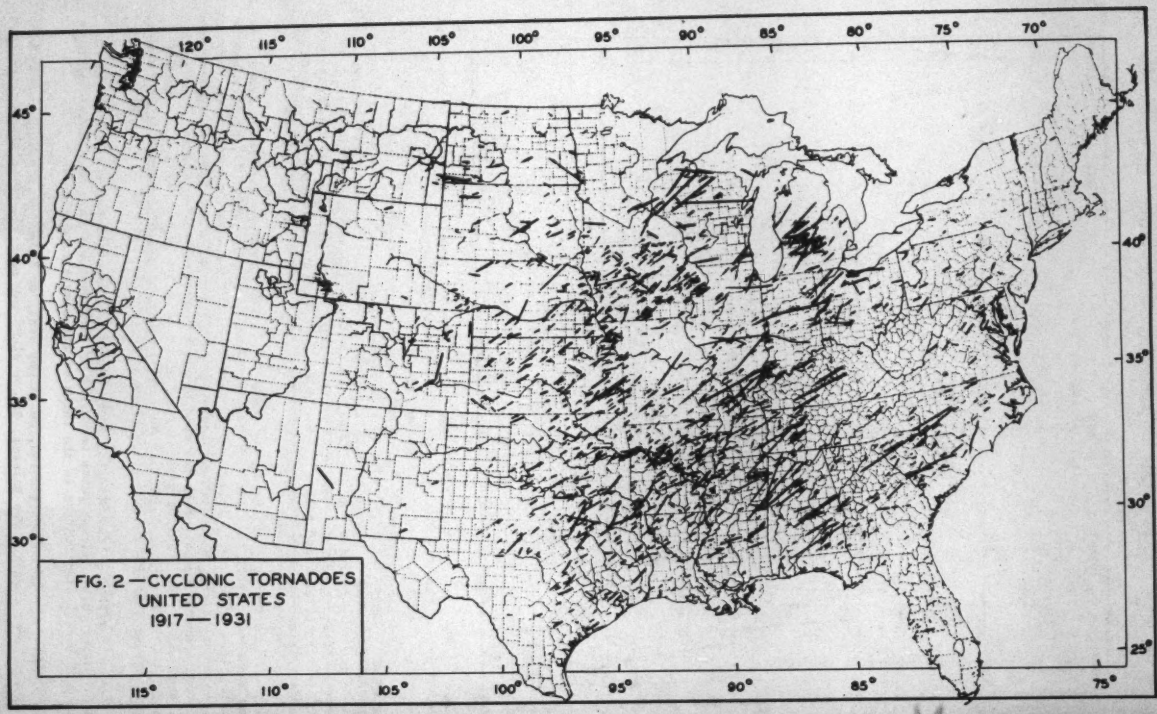
FIG. 1—YEARLY DISTRIBUTION OF TORNADOES 1880 TO 1931

State, as well as the other Plains states, to Iowa and a little eastward to Wisconsin. East of Texas, the high frequency is not so marked in the counties near the Gulf shore-line. From central Louisiana into southern Illinois and then after a gap into southern Michigan, the second belt points northward and includes some of the best marked and longest tracks of this type. The third belt, narrowed on the east by the Appalachians, reaches from central Mississippi-Alabama north to central Kentucky, then with a gap over the breaks of the Ohio, terminates at the western end of Lake Erie. Strongly marked tracks are developed in this zone. The fourth belt is initiated in southeastern Alabama and occurs discontinuously northeasterly through the Piedmont and Coastal Plains region of Georgia and the Carolinas, east of the Appalachians.

The mountainous portions of the states mentioned appear to be comparatively free from tornadoes. With two-fifths of the tornadoes in the 51 years plotted, the northern portions of Missouri, Illinois, and possibly Indiana, have a marked lower frequency, which may disappear when the balance is recorded. In general the convective type is found somewhat to the north and west of the Mississippi Valley states. Though the western belt of the cyclonic tornadoes coincides with the extent of the convective type, yet the major distribution of the most pronounced cyclonic tornadoes is found to the south and east of the convective class.

It is presumably true that the storm-tracks initiated in the lower Gulf region and following their average paths northerly or northeasterly have caused the segregation of tornadic distribution in the belts or zones mentioned above.

Of the 2,017 tornadoes studied, 68.91 per cent, or 1,390, were considered to be of cyclonic derivation. The balance, 627, or 31.08 per cent, occurred under convective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110°
105°
100°
95°
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35°
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FIG. 2—CYCLONIC TORNADOES
UNITED STATES
1917—1931

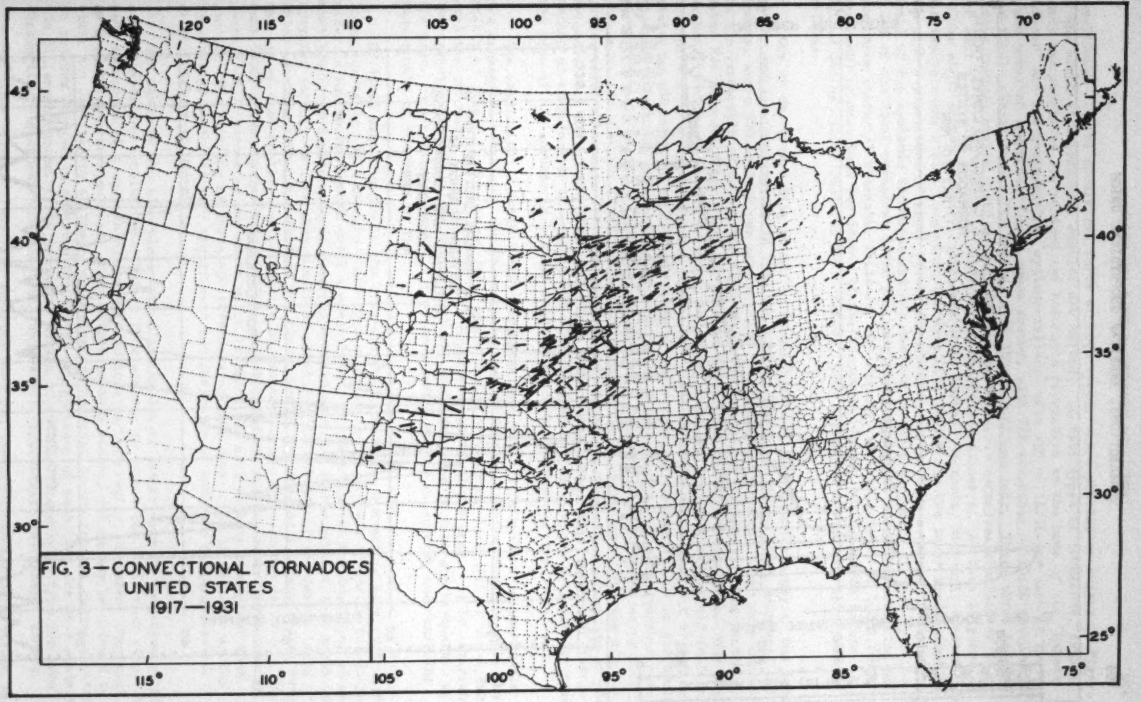
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FIG. 3—CONVECTIONAL TORNADOES
UNITED STATES
1917—1931

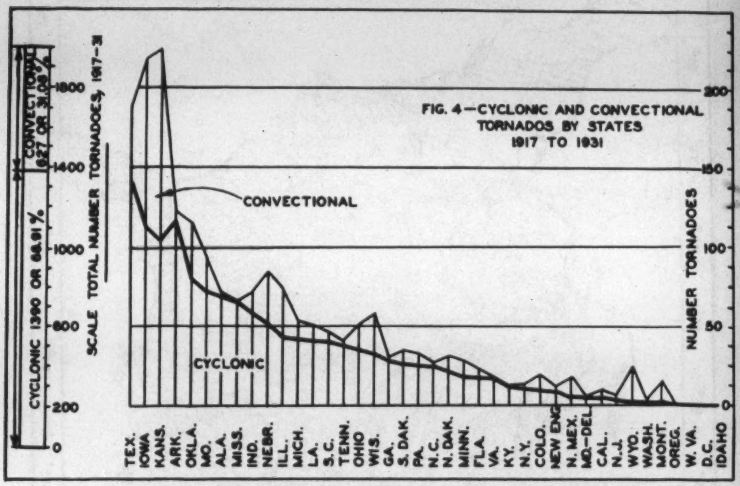

FIG. 4—CYCLONIC AND CONVECTIONAL TORNADOS BY STATES 1917 TO 1931

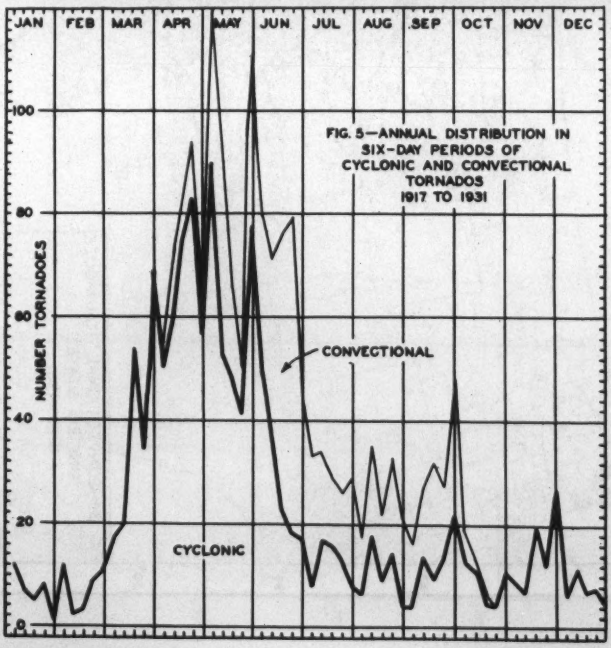

FIG. 5—ANNUAL DISTRIBUTION IN SIX-DAY PERIODS OF CYCLONIC AND CONVECTIONAL TORNADOS 1917 TO 1931

conditions. In the cumulative curve of both types, where plotted by states in Figure 4, the areal distributional results are marked. In both types of tornadoes, Kansas leads and maintains its ancient and honorable reputation as the home of the "Kansas twister" and its accompanying "cyclone-cellar," with 225 or 11.15 per cent of the grand total of tornadoes. Iowa comes second, with 219 tornadoes or 10.85 per cent of the total. Texas is not far behind, with 190 or 9.42 per cent. These three leading states include within their borders 634 out of the 2,017 tornadoes studied, or 31.43 per cent of all the tornadoes occurring in the United States in the last 15 years. In the eight states of Texas, Arkansas, Iowa, Kansas, Oklahoma, Missouri, Alabama, and Mississippi--the states located in the west Gulf region and the lower Mississippi Valley with a population of about twenty-two million people--have occurred 763 (45.1 per cent) of the cyclonic tornadoes and 341 convective (54.2 per cent) of that type, or 1,104 of the total tornadoes (55.2 per cent). If we add 261 tornadoes occurring in the three states of Nebraska, Illinois, and Indiana, we have a total of 1,365 (67.6 per cent) or more than two-thirds of all tornadoes between 1917 and 1931 in the United States, which occurred in 11 states, with a population of about thirty-five million.

One of the interesting points to develop later is the high frequency of the late winter and spring tornadoes in the four leading states of Texas, Iowa, Arkansas, and Kansas, where 480 or 34.5 per cent of that type have been plotted. Even more emphatic is the leadership of Kansas and Iowa in the occurrence of tornadoes in the heated term, for here are found 34.92 per cent or 229 of the convective tornadoes. Why the regionally adjacent states of Texas, Oklahoma, Nebraska, and Missouri should fail to keep pace with these two leading states, it is difficult to say. In these bordering states we add only 141 or 22.5 per cent of the convective tornadoes. It is difficult, also, to understand the rather high ranking of Wisconsin and Illinois, somewhat removed from this region. These two states give a total of 58 more tornadoes or 9.25 per cent. So with the first two leaders with 229 or 34.92 per cent, and the six states added with their 199 or 31.74 per cent, we find a total in eight states of 428 tornadoes out of the 627 plotted or 68.26 per cent. In Figure 5, the annual distribution of tornadoes in six-day periods, one salient fact is brought out, namely, that the type of the tornado is closely confined to certain months of the year.

The conclusion is evident that tornadoes associated with cyclonic disturbances are segregated roughly in the three spring months from the middle of March until the middle of June. In this short three-month period of maximum, occur 912 of the 1,390 cyclonic tornadoes that figure in this report--about 65.61 per cent. It is remarkable that practically two-thirds of the cyclonic tornadoes come in this spring-quarter of the year. The remaining third is scattered rather evenly throughout the remaining nine months of the year.

Of equal significance is the time-distribution of the convective type of tornado. These tornadoes begin to make their appearance in the first part of April, but do not occur in any marked amount until a month later. It is not until the beginning of June that the curve mounts upward, reaching a maximum in the latter part of that month and dropping rapidly to less than a half or third for the balance of the heated term, which seems to show a marked drop the first part of October and a disappearance before the end of that month. The percentage of convective tornadoes in May is 19.62 (123). June (195) shows a percentage of 31.1 and July, August, and September (241) show an average of 80 tornadoes per month which is 12.81 per cent monthly throughout that period. The grouping of these 559 tornadoes of this type or 89.15 per cent in the five heated months is very significant and indicates an entirely different set of causal factors in operation.

The study of the time-place-type distribution of either type of tornadoes promises some interesting conclusions. Though from analogy we cannot say positively since so many tornadoes of a certain type are found in a certain region, therefore they must, or a certain proportion must, occur within certain months, yet we may be allowed to state the probability of their occurrence as indicated by the general curves plotted. We are now engaged in studying the curves of frequency of each type for each state for the different months. From tentative curves of monthly frequency of type for some states it would appear that the local curves will approximate the general curves.

If Texas, Kansas, Iowa, and Arkansas have 280 convective tornadoes or 44.65 per cent of that type, or 13.88 per cent of the total and 89.15 per cent of that type

occur between May and September inclusive, the chances are that these states will have had 150 tornadoes in the 15-year period or 89.15 per cent of any one year within that period.

Again if these four states have had 480 cyclonic tornadoes or 34.53 per cent, or 23.74 per cent of the total, and from March to June occur 65.61 per cent we might expect two-thirds in any one year or 315 for the 15-year period. Combining the above probabilities, we might expect in the seven months from March to September inclusive 465 tornadoes, or an average of 31 yearly in that period in those four states for the 15-year period. On a percentage basis, if proportion holds for the 51-year period, Texas, Kansas, Iowa, and Arkansas should expect 23.54 per cent of all the tornadoes in the United States yearly and in those seven months. The economic significance of these figures for storm-insurance premiums is suggestive.

To say that these two types would occur in any region in the westerlies would probably be somewhat from the truth, and it may be that international cooperative studies may indicate that the high frequency of the winter cyclonic disturbances in the United States may be sui generis on account of the unique land and water and ocean-current conditions in this country.

In particularizing, it is necessary to recognize that the eastern two-fifths of the southern border of this country opens out as a low coastal plain upon a tropical or subtropical Mediterranean Sea--the Gulf of Mexico. Along the shores of this southern, as well as the southeastern coastal plain of the United States, flows the heated water of the Gulf Stream. Another major factor lies in the considerable distribution of lands to the north and west of the Mississippi Valley, which may produce extensive flow from high-pressure areas of winter-chilled air in a southeasterly direction. These two prime factors have been, on the whole, the major influences in determining the frequency of time-, areal-, and type-distribution of United States tornadoes. The inrush of unusually warm and moisture-laden air with the southerly winds from the Gulf region presumably tend to give the lobate shape to cyclones in the lower Mississippi region. This tendency, moreover, was highly exaggerated by the concurrent development of a high-pressure area to the northwest.

It is evident that these conditions cannot be duplicated in the Mediterranean Sea of Europe, where, although we have the relatively warm waters even without an ocean-current, yet we have no large extensive lowland plains or poleward land-mass opening to the southward on a warm water-body.

Again, one other region in the westerlies of the Argentine is diametrically opposite with reference to the above conditions. The land-mass tapers rapidly poleward and broadens toward the equator. No warm subtropical Mediterranean is found on the equatorial side of the Argentine. Once more, not enough land exists poleward of the tropical calms in Australia nor is it open to the warm equatorial sea-winds, on account of the range of coastal mountains, nor is the wide expanse of land developed poleward. That leaves but one region, that of southeastern Asia, that approaches in a feeble way in southern China, the possible conditions that exist in the United States. It would seem, therefore, that we are dealing with a unique plexus of meteorological conditions that result from an equally unique topography and arrangement of land and warm seas, which give rise to the formation of a rather large number of severe whirling-disturbances in the lower Mississippi Valley in a critical period of the year, that is, the late winter and early spring.

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COMMENTS ON THE GENERAL CIRCULATION

R. Hanson Weightman

These comments are given as a discussion of the item proposed by the American Geophysical Union for the agenda of the Lisbon Assembly.

The general circulation is of course a very broad subject but in its major as well as in its collateral aspects is one in which we are all greatly interested.

There are two phases which have specially drawn my interest and they are both inherently associated with the general circulation.

The first is the increase and decrease in the central pressure of high-pressure areas or anticyclones. There are many cases in which Highs in North America increase considerably and others in which they decrease considerably. There is a much smaller number in which the pressure in an anticyclone increases from below normal in the course of several days to 30.50 inches or more, and others where the central pressure in them decreases from 30.50 inches or more to below normal. Of the first class I would like to cite an example, namely, that of December 21-25, 1931. In this case there was a low-pressure center over northeastern Hudson Bay with lowest pressure at Nottingham of 29.04 inches, and another disturbance over western Alaska (Nome 28.80 inches) with a trough extending southeastward to British Columbia (Kamloops 29.30 inches). Between these Lows, pressure was indifferently higher, the highest being 29.76 inches at Fort Smith, Northwest Territory, but with low temperatures, -36° F, at Coppermine. During the next 12 hours pressure rose to 29.86 inches at Coppermine and during the succeeding 12 hours to 30.06 inches at Churchill and to 29.90 inches at Coppermine. By the morning of December 23, Churchill had risen to 30.16 inches and Coppermine had fallen to 29.50 inches. On the morning of December 24 pressure at Churchill had risen to 30.44 inches, at Chesterfield Inlet to 30.12 inches, and at Nottingham to 30.14 inches. The center then moved southeastward with further increase of pressure to 30.48 inches at White River by the morning of December 25. By the following morning the center was over eastern Ontario with greatest pressure at Doucet (30.68 inches). From the evening of December 23, when the highest central pressure was 30.36 inches, surface-winds from the area north of Hudson Bay were completely cut off and while we have no report north of Chesterfield Inlet there is some doubt whether surface-wind from the north prevailed during the early days when the greatest central pressure was only 30.06 inches. The question is, why does the central pressure of the anticyclone increase so markedly? Of course we know that there must have been a transfer of colder, denser air over the region of Churchill at some level. This was true at the surface during the earlier stages of the increase in pressure. The temperature fell from 8° F, just preceding the time of the surface-shift of wind from south to northwest, to -38° F on December 24, a.m., when the highest pressure (30.44 inches) occurred at Churchill. It was at that time, however, that the northerly winds to the north of the center of the High, that might be expected to maintain and build up the High, were no longer in evidence, having given place to southwest and west winds. In spite of the fact that the northerly current had been cut off, the central pressure of the High further increased during the subsequent 48 hours to 30.68 inches. The question is at what level is the denser air transported to the region of the High?

The second point is in a way associated with the first. It deals with larger-scale operations, probably involving both the northern and southern hemispheres. Cases are found in seasonal correlation of conditions in widely separated regions, such as those carried out by Sir Gilbert T. Walker in "World Weather V," published in the Memoirs of the Royal Meteorological Society (v. 4, No. 36). Previous to the appearance of this work, I had compared temperatures in the northeastern states, as represented by 10 stations with pressures at 60 widely distributed stations throughout the world. These showed that winter temperatures in the northeastern states had correlation-coefficients with preceding March, April, and May pressures combined as follows: Manila +0.41, Batavia +0.51, and Darwin +0.46. After numerous trials with multiple correlation-coefficients of winter temperatures in the northeastern states with pressures 1 quarter, 2 quarters, and 3 quarters before, it was decided to take the four coldest winters--1889, 1898, 1912, and 1918--and the four warmest winters--1890, 1899, 1913, and 1919--in the northeastern states and to make charts showing pressure-departures at the 60 world stations 1 quarter, 2 quarters, and 3 quarters before. This was done, but even with these extreme cases there was little conformity in any quarter of the globe for the warm types or for the cold types. The question is, why should this be?

Apparently the channels that bring us cold winters are not the same. In some cases the antecedent conditions show plus departures in the region of the East Indies and Australia, and in others just the reverse. In studying surface-conditions as shown by the northern-hemisphere maps, we know that in some cases we have outbreaks of cold polar air over western Europe, and in others over different parts of Canada.

May it not be that we have breaking through, we might put it, in higher levels in one place preceding one cold winter and in some other place in another cold winter? At the surface we have natural barriers such as mountains, as well as ocean-currents and ice- and snow-cover to affect conditions. May it not be that we have similar agencies in the free air as well?

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AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Washington, D. C.
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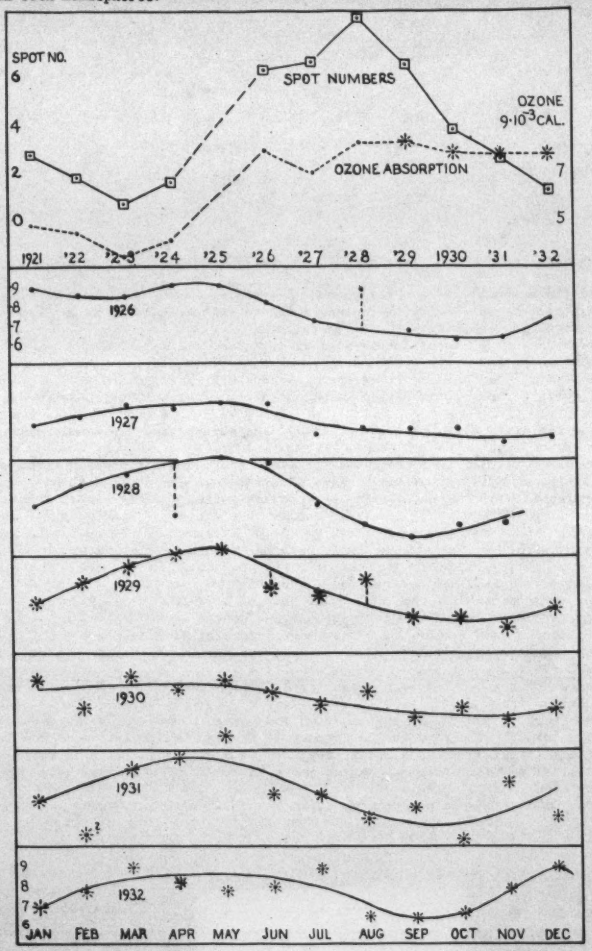
OZONE AND THE SUNSPOT-CYCLE

Frederick E. Fowle

The ozone under consideration lies in a layer some 50 kilometers above sea-level. It may, in diminishing quantity, extend down to 20 or up to 80 kilometers (Chalonge, 1932). The means used in the measurement of its altitude do not lend themselves to great accuracy. Its amount varies from about 2 to 4 mm when brought to the standard conditions of 76 cm of mercury pressure and 0° C. The maximum amount occurs in the spring in both hemispheres.



The measurements here treated were made in the Chappuis yellow band. This band is too shallow to be distinguished in an optical spectrum. In a solar-energy curve it is masked by the dominant solar lines. However, if the atmospheric transmission-coefficients are determined for each deflection in the solar-energy curve and plotted against either wave-lengths or prismatic deviations the solar lines will have disappeared whereas atmospheric lines, including the lines due to ozone, will stand out in beautiful detail (see Atmospheric ozone, Smithsonian Miscellaneous Collections, 81, No. 11, 1929). The results are finally expressed as the number of calories deleted by this band from the incoming solar energy when the Sun is in the zenith. This datum rarely exceeds 10^{-2} calory.

In the upper section of the accompanying figure will be found a graph with square points indicating the run of the mean annual Wolfer sunspot-numbers for the days upon which ozone-observations were made and for the years 1921 to 1932, inclusive. The next lower curve shows yearly mean ozone-values. It is based upon the observations of some 900 days. The dots from 1921 to 1928, inclusive, of my earlier paper (l. c.) show a decidedly close correspondence with the sunspot-graph. The starred points for newer years show a (to me disappointing) decided lack of correspondence.

The observations in the lower rectangular sections show the run through the years of the monthly means. The base-line of each rectangle corresponds to 5×10^{-3} calory per minute, the upper line to 10^{-2} calory. They well depict the yearly march of ozone. No convincing reason has yet been proposed for the cause of the spring maximum and the fall minimum. No further discussion of these will be undertaken in this presentation.

Conclusions--Prima facie, the new results do not confirm a dependence of the amount of ozone in our atmosphere upon solar conditions as roughly indicated by the sunspots. This situation may be worthy of further comments:

(1) The observations do not extend over a complete spot-cycle which is now known to be double the time formerly allotted to it, some 22 instead of 11 years; there are differences in the polarities of the spots in the two halves of the longer period.

(2) There has been a tendency among some to suppose the amount of ozone to be due to the ultra-violet light of the Sun; others would connect it with the auroral discharge. It might owe its origin to the bombardment of the Earth by particles of some kind. The first two causes we know to be closely connected with the sunspot-cycle.

(3) Unfortunately the observations were not all made at the same station. The low values of 1921-24 came from Harqua Hala; a close examination reveals no hope of raising them. There are days where practically no absorption is present. The observations of 1926-28 were made on Table Mountain. There can be no doubt of the larger absorption.

One might suggest a latitude-effect as the amount of ozone is known to increase with higher latitudes; but the difference of latitude between the two stations is small with Harqua Hala in latitude 33° 48' north at altitude 1,721 meters, and Table Mountain in latitude 34° 22' north at altitude 2,286 meters. Notably this falls in the region where Compton finds the greatest increase in the ionization due to cosmic rays. Any altitude-effect would be expected to make the ozone above Harqua Hala greater rather than smaller than that at Table Mountain.

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SOME RECENT EARTH-RESISTIVITY MEASUREMENTS IN THE UNITED STATES

R. H. Card

Introduction--The problem of constructing and maintaining in the same region networks of lines for the transmission of power and of intelligence in such a way as to minimize the electrical interference between these two types of facilities is of a com-

plicated nature. One of the controlling factors in determining the severity of any situation may be the effects of currents returning through the Earth. In power-supply systems, as usually designed and operated, the current in the Earth under normal conditions is quite small, but occasionally short circuits to ground occur which increase this current sometimes to hundreds of amperes. In electrified railways a substantial portion of the propulsion-current returns to the source through the Earth, and as in power-supply systems, this earth-current may be greatly increased by short circuits to ground.

These earth-return currents may produce, by inductive or conductive action, voltages in nearby communication-lines. One of the parameters of the mutual impedance between the power- and communication-lines, or the ratio of the resultant voltage to the earth-return current, is the resistivity of the Earth at the location in question.

In many situations of this character the mutual impedance between existing lines is measured at the frequency of the power-system and from this measurement and a knowledge of the physical relations between the lines, the earth-resistivity may be derived. In other instances the earth-resistivity is determined from measurements made in special test-circuit layouts and the value so obtained used in calculating the mutual impedance between existing or projected lines.

Measurements of both the above types have been made in various parts of the United States by the American Telephone and Telegraph Company and its Associated Companies in cooperation with various power-companies and with railroad companies having electrified sections of line. Other measurements have been made by the Joint Sub-Committee on Development and Research of the National Electric Light Association and the Bell Telephone System. This paper presents briefly the earth-resistivity values derived from a considerable number of these measurements.

Methods of measurement--A brief description of the methods of measurement used will be of assistance in interpreting the results to be given. A more complete description will be found in a paper by Messrs. Bowen and Gilkeson (Mutual impedances of ground-return circuits, Trans. A.I.E.E., v. 49, 1370-1379, 1930).

These methods may be considered under three general classifications, namely, (1) mutual impedance-measurements between existing lines, (2) alternating-current exploring-wire tests, and (3) direct-current exploration-tests.

The majority of the values to be given were derived from measurements of the first type--mutual impedance-measurements between existing lines, in most instances between a power-supply line and a communication-line. For such tests one or more of the wires of the power-line are connected to form an earth-return circuit extending through the section involving the communication-line. This circuit is energized from a suitable source of power at the fundamental frequency of the power-system, usually 60 cycles per second, and the current is measured. One of the communication-line wires is likewise connected as a ground-return circuit, and the induced voltage in this circuit is measured.

The mutual impedance determined from these measurements is then compared with values of this impedance calculated for a series of assumed values of earth-resistivity. By interpolation, the "effective" earth-resistivity corresponding to the measured mutual impedance is found. Methods of making such calculations are described in detail in Engineering Report No. 14 of the Joint Sub-Committee on Development and Research of the National Electric Light Association and the Bell Telephone System (Engineering reports of the Joint Sub-Committee on Development and Research, v. 2, 121-186, 1932).

The second method, using exploring wires and an alternating-current source of testing power, is in principle similar to the first. Usually an existing line of considerable length is energized as a ground-return circuit: At one or more selected points along this line comparatively short exploring wires are laid on the surface of the ground parallel to the energized wire and at several different separations from this wire. The voltages induced in the exploring wires, connected as ground-return circuits, are measured and the mutual impedances, which are the ratios between the measured voltages and the current in the energized wire, are determined. The group of

observed mutual impedances are then compared with values calculated for a range of earth-resistivities, and an effective resistivity is thus determined.

The direct-current exploration-method used is similar to the familiar methods employed in such work as geophysical prospecting, differing only in detail, for instance, from that described by Messrs. Gish and Rooney (Measurement of large masses of undisturbed earth, Terr. Mag., v. 30, 161-188, 1925). None of the values to be given was obtained primarily by measurements of this type. In several instances, however, the results of the alternating-current tests have been checked, at least partially, by direct-current measurements.

Test-results--In the cooperative work of the communication- and power-companies of this country, it is customary to express earth-resistivities in terms of the meter-ohm and the values to be given below will be so expressed.

The results of the tests analyzed to date have shown effective earth-resistivities ranging from a minimum of 2 meter-ohms to a maximum of 10,000 meter-ohms. The following Table gives the distribution of the measured values among various resistivity-ranges.

Effective earth-resistivity	Number of tests	Per cent of total
2 to 10 meter-ohms	16	12
11 to 100 " "	47	35
101 to 1000 " "	45	34
1001 to 10000 " "	25	19
Totals	133	100

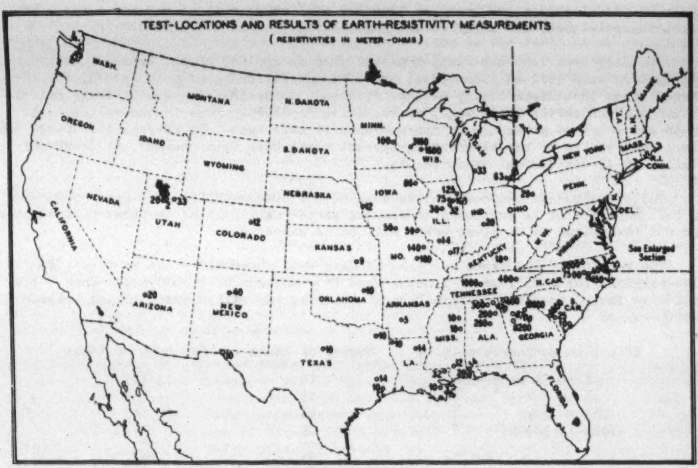
The measurements from which these results were derived were made at random locations, no attempt having been made to make a systematic survey of the country. Consequently, the distribution of values given in the above Table may be quite different from that which would be shown were the Table to be based upon the areas of the regions in which the various ranges of values might be expected to obtain. In fact, it seems likely that a table of the latter nature would show a smaller percentage assignable to the higher ranges. This is based upon the assumption that, other factors being equal, the mutual impedance between communication- and power-lines is greater in regions of high resistivity, the likelihood of interference is thus increased, and there is consequently a tendency to make a larger number of tests in such regions.

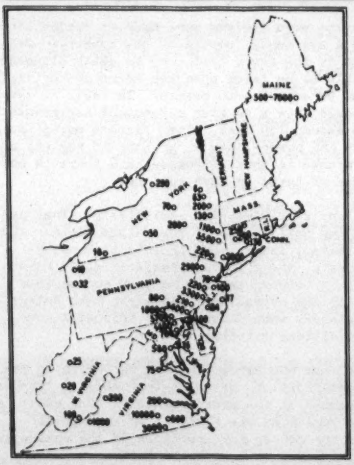
Geographical distribution of measured resistivities--The resistivity-values determined have been plotted on the accompanying outline map of the United States. For each test, the approximate location is indicated, and a value of effective earth-resistivity is given. In the majority of tests, the effective resistivity is determined by analysis of the measurements as lying between certain maximum and minimum values; in such instances the figure given is the approximate geometric mean between the maximum and minimum, except in some instances when judgment has indicated some other value to be more indicative of the conditions existing.

In connection with the investigation of any one situation, the variation in resistivity along a considerable length of communication- or power-transmission line is sometimes determined. In presenting the results of the measurements in such cases, a single representative value is given if the variation was found to be immaterial. Where the variation was significant, values for two or more portions of the entire section are given, each of such portions being treated as a separate test.

In a few instances, particularly in New Jersey, when several tests in the same general vicinity have shown approximately the same resistivities, the results of only one of these tests are shown on the map. For this reason, it will be found that the total number of tests plotted on the map is somewhat less than the total previously given.

Considering the geographical distribution of the values shown on the map, it will be noted first that, as shown by numerous tests, a comparatively narrow band of high resistivity, probably broken in some sections, seems to extend from New York to Georgia approximately parallel to the Atlantic coast line but some distance inland. The re-





sistivities within this band range from about 1,000 to 10,000 meter-ohms. In the one test made in Maine, the results varied between wide limits within the test zone. The values given on the map for this test, 500 to 7,000 meter-ohms, represent the extremes of the variation. Both alternating-current and direct-current tests were made and both seem to have shown that some high-resistivity material is present in this region. No test-data are available to indicate whether high resistivities will be found between this point and New York. Also, no data are available to indicate whether this band extends southwest of the Georgia-Alabama State Line.

The eastern edge of the high-resistivity band just mentioned has been established by measurements at number of locations as lying approximately along the western edge of the Atlantic coastal plain. Toward the east from this dividing line the resistivities drop off rapidly, changing from several thousand meter-ohms to values ranging from 25 to 500 meter-ohms within distances of only 10 to 25 miles. Farther to the east, just back of the coast line, two tests, in New Jersey and South Carolina, showed values of 17 and 10 meter-ohms, respectively.

The western edge of the high-resistivity band has not been so well defined. It can be said, however, that it seems to lie within or just to the east of the Appalachian Mountains, as shown by the measurements indicated on the map in central Pennsylvania, along the Virginia-West Virginia State Line, eastern Tennessee, north Georgia, and northeastern Alabama. Most of these latter measurements have shown values of 200 to 470 meter-ohms, two of the remainder being about 100 meter-ohms and one 1,000 meter-ohms.

Farther to the north and west of the Appalachians, the values are too scattered to permit of any generalizations as to particular geographical regions. With the exception, however, of a few tests in northern New York State, northeastern Illinois, central Tennessee, east-central Missouri, and Wisconsin, they have all shown values of 100 meter-ohms or less. The outstanding exceptions are two tests made in Wisconsin which have indicated the presence of another high-resistivity region, the values indicated being 1,800 meter-ohms and 3,160 meter-ohms, respectively.

It is of interest to note that in a test in the salt-flats close to the southeastern shore of Great Salt Lake the lowest value of this series of tests, 2 meter-ohms, was indicated. Immediately to the southwest on higher ground an increase in resistivity to a value of 20 meter-ohms was indicated.

Interpretation of results--Mention has been made of the analysis of the results of the alternating-current tests by comparing the measured mutual impedances with calculated values. The formulae used for these calculations assume the Earth to be a homogeneous semi-infinite solid of uniform resistivity. The earth-resistivity thus derived is then an "effective" uniform value for the frequency at which the measurements are made. Actually the Earth is a complex structure, usually consisting, at least in the upper portions with which we are concerned, of strata of many different kinds of material. These strata may be horizontal, inclined at any angle, or folded and faulted in complicated manner. The rocks composing these strata contain varying amounts of water and the composition of the water may vary widely. It will be seen that the effective earth-resistivity is in the nature of a weighted average value of the resistivities of these various strata.

When the stratification consists of a layer of material of uniform resistivity and thickness superimposed on a semi-infinite uniform medium of a different resistivity, it can be shown from theoretical considerations that for a given frequency, it is possible, by proper choice of a value of effective earth-resistivity, to construct a calculated curve showing mutual impedance versus separation between disturbing and disturbed conductors, based upon a homogeneous Earth, which will quite closely match a similar curve calculated on the basis of the actual Earth-structure. If the strata in such a case are of different resistivities, it will be found that the "effective" resistivity will be different for different frequencies. At least within the range of frequencies employed in these tests, the effective resistivity decreases as the frequency is increased if the upper layer is of lower resistivity. The opposite holds true if the upper layer is of higher resistivity.

Calculations for such a two-layer structure indicate that for a frequency of 60 cycles with an upper layer having a resistivity of 1,000 meter-ohms, a lower layer of 10,000 meter-ohms resistivity would not increase the effective resistivity of the combination more than 50 per cent unless the dividing plane between the two layers were at a depth of about 3,700 feet or less. The corresponding depth for an upper layer of 30 meter-ohms with a lower layer of 3,000 meter-ohms is about 1,100 feet. These and other examples that could be given show that the resistivities indicated by the alternating-current measurements are not largely affected by the structure of the Earth below a depth of the order of 1,000-4,000 feet and in cases where the effective resistivity is found to be small it may be affected by the Earth-structure to a considerably smaller depth.

Detailed data concerning the structure of the Earth for a majority of the test-locations, and general geological data for the remainder, have been secured and it is hoped that a paper discussing the correlation between these data and the test results can be published later this year.

Acknowledgment--Thanks are due the various organizations that have cooperated in making the tests upon which these data are based. The suggestions and criticisms of my associates in the Bell System are also gratefully acknowledged.

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MAGNETIC ANOMALIES IN ALASKA

E. W. Rickelberg

Magnetic anomalies are the rule rather than the exception in Alaska, particularly in southeastern Alaska. Observations taken by Coast and Geodetic Survey parties indicate the presence of local disturbance all along the coast from Dixon Entrance at the southern extremity to the Bering Sea. St. George Island in the Bering Sea shows variations ranging from 6° east to 20° east, 17° east being normal.

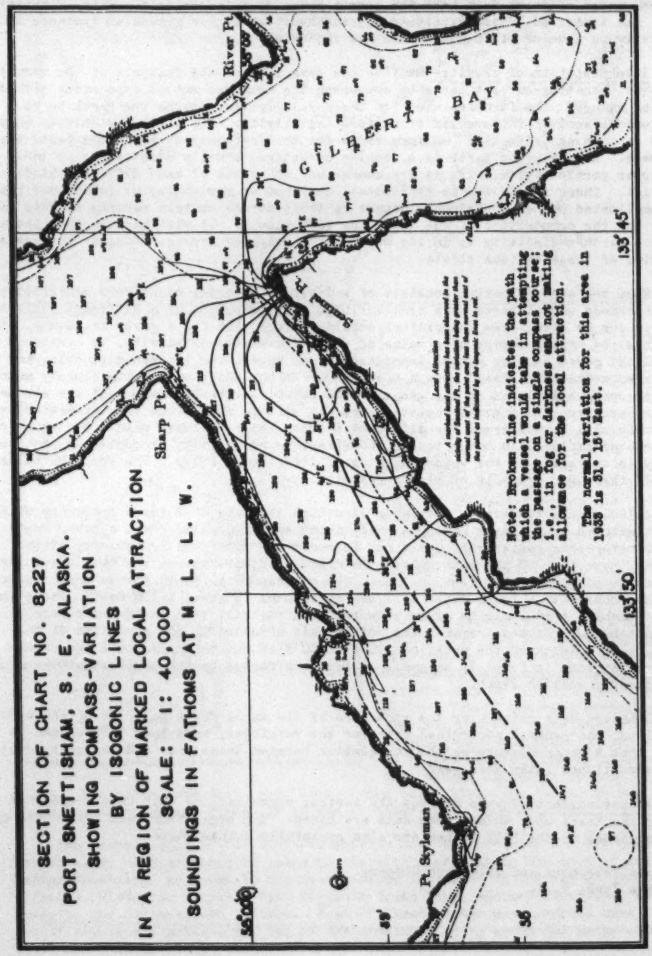

SECTION OF CHART NO. 8227
PORT SNETTISHAM, S. E. ALASKA.
SHOWING COMPASS-VARIATION
BY ISOGONIC LINES
IN A REGION OF MARKED LOCAL ATTRACTION
SCALE: 1: 40,000
SOUNDINGS IN FATHOMS AT M. L. L. W.
GILBERT BAY
River Pt.
Sharp Pt.
Pt. Sylvester
Note: Broken line indicates the path which a vessel would be instructed to pursue on a direct course; i.e. in fog or darkness and not making allowance for the local attraction.
The normal variation for this area in 1933 is 21° 15' East.
135° 45'
135° 50'
58° 45'

Fig. 1

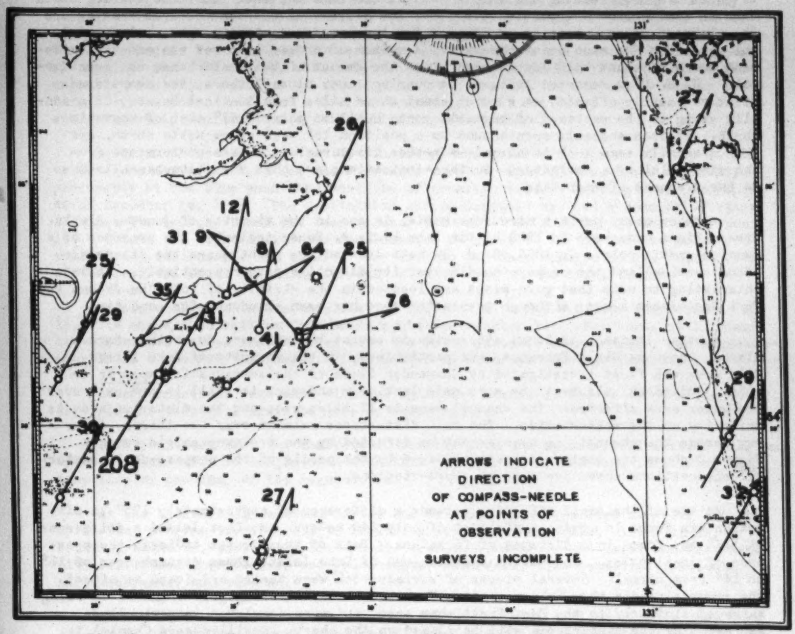


Fig. 2--Compass directions, entrance to Dixon Entrance, Alaska

In western Alaska, on the Aleutian Peninsula, disturbances have been found, but are not fully developed. This will be done as the surveys of that area are completed. Chilkoot Inlet, southeastern Alaska, has variations ranging from 12° to 37° east, the normal being 32° east. Union Bay, southeastern Alaska, has variations ranging from 32° to 68° east, the normal being about 30°. At many places the disturbance extends out over the water-areas in sufficient strength to affect the compasses of passing vessels. Wherever the surveys are sufficiently complete these disturbances are indicated on the navigation charts by local isogonic lines printed in red over the area affected.

One very good example of such an area is at Port Snettisham, southeastern Alaska. This passage is 1-1/2 miles wide and 120 to 130 fathoms deep. Figure 1 shows the danger of such areas to vessels navigating in a fog or in darkness. The broken line is the path of a vessel following a mid-channel course, if there were no disturbance. The solid line is the path resulting by a vessel steering the same compass-course as before, for example, in fog or darkness, and not aware of the local attraction. The vessel would be driven ashore.

A rather complete survey of this area was made by N. H. Heck of the Coast and Geodetic Survey. In this survey 34 shore-stations were occupied with compass-declinometer and 111 sea-stations were observed on board the survey-ship Explorer. For the observations at sea a system of lines was run, the vessel proceeding at a speed of about six miles per hour. As the compass could not be used for keeping the vessel to its path, the method of steering for a point ahead was adopted. Compass-bearings and angles for determining the ship's position were taken at intervals of two

to three minutes, reading the ship's head at the same instant. The true bearing could then be scaled from the plotted position; the difference between the true bearing and the observed compass-bearing, corrected for the compass-deviation, gave values of local variation for each point observed. A system of cross-lines was run and the agreement was within one-half degree even where the amount of the disturbance was considerable. N. H. Heck reported that, while running lines close inshore, the compass was first noticeably affected at a point about three miles from Sentinel Point. It gradually swung to the eastward of magnetic north until it pointed 41° east of magnetic north. It then suddenly spun around to a position 15° west of magnetic north, and then gradually came back to normal--a rather discouraging compass-performance from the standpoint of a navigator. Surface-indications are that the disturbance is due to the presence of magnetite.

Another case, perhaps more remarkable, is one in the vicinity of Juneau, Alaska. Observations made here in 1900 by the late Louis A. Bauer indicated the presence of a local magnetic pole. In 1903, S. J. Barnett located the point where the dip-needle stood vertical and the compass-needle lost its directive property entirely. It is interesting to note that gold mines are located in the vicinity of both the Juneau and Port Snettisham areas, although the latter mine has been abandoned for some time.

Another instance of local attraction is one at the entrance to southeastern Alaska, known as Dixon Entrance, and particularly in the vicinity of Duke Island. This area was first investigated by Commander Siems of the survey-ship Explorer in 1924. Additional observations were made last year and work is still in progress over the water area affected. The channel here is 12 miles wide and the disturbed area is primarily on the western side. The main disturbance extends over two-thirds of the way across the channel, as near as can be detected by the ordinary ship's compass. Figure 2 shows the various directions taken by the needle of the compass-declinometer. All observations shown are made at shore-stations.

At one of the small off-lying islands a difference of approximately 177° in direction was found in moving a distance of only 240 meters. At East Island a difference of 117° was found in a distance of 75 meters. Both of these cases indicate the presence of local poles. The entire southern end of Duke Island shows disturbances of 12° to 14° from normal. Several pieces of surface-rock were tested and found to affect the compass-needle when held near it. The water-area, Revillagigedo Channel, is being surveyed similarly to the Port Snettisham area, and when completed, isogonic lines representing the disturbance will be placed on the chart. Revillagigedo Channel is the main entrance-channel to southeastern Alaska. Duke Island is a rather low, hilly island and quite different from most of the more rugged country of southeastern Alaska, where magnetic disturbances are found. The topography here is of great natural beauty, the deep channels being flanked by mountainous sides and being usually heavily wooded to about 2,000 feet elevation.

U. S. Coast and Geodetic Survey,
Washington, D. C.

PROGRESS-REPORT ON THE WORK OF THE CANADIAN MAGNETIC OBSERVATORIES

W. E. W. Jackson

The fact that the magnetic pole is situated in Canada has placed Canada in a unique position in relation to the Polar-Year program. It was very unfortunate that economic conditions should have been so adverse, but nevertheless our Government voted the necessary credits for Canada to establish a fully equipped magnetic observatory at Chesterfield Inlet, and F. T. Davies, who was very graciously granted furlough by the Carnegie Institution of Washington, Department of Terrestrial Magnetism, was placed in charge.

He arrived at Chesterfield on August 13, 1932, and immediately began the erection of the Observatory. On September 2 he reported the magnetic hut completed and the la Cour recording-instruments were being installed, and on September 15 he was securing photographic records on the low-sensitivity, ordinary-sensitivity, and quick-run magnetographs.

Quoting from his report of September 25, "The declination is dancing a lively tune--I think the fast recorder will frequently prove puzzling to follow, as the declination traces look as if a small army of inky-legged flies has crawled over the paper. The disturbances in horizontal force and in vertical force are nothing like as great or rapid so far. Of course, with only ten-days' records in hand I cannot state the magnetic conditions definitely. The declination, however, is subject to almost continual disturbance. Have had a declination-range of 4° and every day from 1° to 3° and quite rapid oscillations showing all along the traces."

In December he reported that he considered the quick-run records of very little value since during disturbance the movements were so rapid that no trace was left, presumably at the time when they would be of greatest value. Quoting from his report dated December 26, 1932, "The declination during December has had a mean daily range of about 4°, though it has not been greater than 12°. On November 16 the range was 16°. I have the high-sensitivity declinometer at about 1' per mm and the low-sensitivity declinometer at about 1° per cm. So far have managed to get one or other of the reserved spots recording for each element even in bad disturbances."

Absolute observations of declination are made with D.T.M.C.I.W. magnetometer No. 15, with check observations from Smith portable magnetometer. For horizontal intensity, absolute values are obtained with the Smith portable magnetometer, and magnetometer 15 is a reserve instrument. Inclination is observed with our inductor 2.

Intercomparisons were made with the Agincourt standards before shipment to Chesterfield and they will again be made on their return.

I am confident that the analysis of results from the Chesterfield station will be of very great value in conjunction with that of other polar stations in solving the many complex problems of the magnetician.

At the Chesterfield station Davies and his assistants are also carrying out the Polar-Year program in meteorology, including synoptic chart-data, kite-flights, sounding-balloons, cloud, temperature-differences between ground-level and mast-head with resistance-thermometers and galvanometer-recorders, also potential gradient, earth-currents, and aurorae.

It may be of interest to note that in connection with balloon-flights they were successful in getting several very long flights, one flight was followed for 138 minutes reaching an elevation of approximately 25 kilometers.

Continuous photographic records of earth-currents have been obtained since the middle of September. In regard thereto Davies says "The earth-current records are extremely disturbed--high frequency and great range, the range being many times the order of variation we read of in the literature on the subject, reaching 200 to 300 millivolts per kilometer. We have examined the general trend of the magnetic and earth-current traces and find quite close agreement particularly between the declination and earth-current traces. On several occasions bright aurorae coincided with increased magnetic and earth-current activity."

In addition to the visual and spectroscopic auroral observations, arrangements were made for a two-station photographic program, using Störmer cameras. A secondary station was established about 20 miles south of Chesterfield and has been occupied on several occasions by Currie for a week or ten days, at a time, and Davies reports on March 27, 1933, that they now have one thousand parallactic photographs from each station and about one-third provide good data.

Through the kindness of the Physics Department, University of Toronto, a spectrum-camera was placed at the disposal of the Chesterfield party and they are securing spectrograms of the aurora every night. Even when cloudy an exposure of two hours brings out the auroral line. Spectra are being secured with both panchromatic and infra-red plates.

Reporting on frequency of aurorae in his December 26 report, Davies says "The previous reports of auroral frequency from here and Churchill are evidently very much underestimated for aurorae can be seen on nearly every clear evening, though there is

a very marked variation in activity from one period to another. We have usually noticed auroral activity quite consistent for nearly two weeks on end followed by a few days of very quiet conditions and then another fairly long period."

Photographs of aurora are taken at Chesterfield on all possible occasions in addition to the two-station work.

Two other special polar stations have been established by Canada, particularly for meteorological work; one at the mouth of the Coppermine River on the Arctic Coast, in charge of R. C. Jacobsen, is specializing in aerological work with pilot-balloons, radiosondes, flashing meteorographs, and kites. Flights with pilot-balloons of half an hour or more have been quite rare, due to the considerable frequency of low clouds. Thirty-five kite-flights had been made up to January 31, 1933, and Jacobsen reports at least half record temperature-inversions up to 8° C. Radiosondes have not yet proven their value, and up to January 31 the results were nil. On February 28 one was successful, being followed to a height of nine kilometers at which point temperature was 245° absolute but was not steady, fluctuating 6°; on March 4 another, which reached steady temperature of 230° absolute at 9.6 kilometers, was followed.

Auroral photographs are also made at this station in accordance with the time-scheme for single stations and at other times when the aurora is particularly striking. A few over a hundred plates were taken up to the end of January. Jacobsen reports "The auroral displays to the south and southwest predominate. Sudden extensive outbreaks in the south working up overhead very quickly sometimes reoccur on several successive nights at nearly the same hour."

Regular meteorological observations for synoptic charts are also made at Coppermine as well as earth-temperatures, sunshine-records, ground-temperatures and mast-top temperatures with resistance-thermometer, photographs of snow-crystals, clouds, and other occasional phenomena.

The other station at Cape Hope's Advance in Hudson Straits is in charge of J. E. Lilly, and in addition to securing synoptic chart-data and regular meteorological observations he is making balloon-flights and photographing aurorae. Up to March 3, 1933, he reports having made 244 balloon-flights--maximum duration 76 minutes--and having exposed 162 auroral plates with satisfactory results.

Our permanent magnetic observatories are carrying on as usual. The absolute observation of horizontal intensity at Agincourt with the Schuster-Smith magnetometer continues to be of the same order of excellence as reported in the Journal of Terrestrial Magnetism and Atmospheric Electricity of March 1932, and the other instruments are all functioning well.

The equipment at the Meanook Observatory was increased by the addition of the la Cour magnetographs (low sensitivity, ordinary sensitivity, and quick-run), which were housed in a separate non-magnetic building, and well insulated to reduce as far as possible the diurnal temperature-variations.

The regular Kew-type magnetographs are also being kept in operation in order to insure continuity of results. Records from the la Cour equipment commenced at 0 hour G.M.T., August 31, 1932.

In view of the activity in the magnetic field at Chesterfield, it is worthy of note that at Agincourt the mean diurnal-range derived from the 24-hourly values in both declination and horizontal intensity for the last four months of 1932 are the lowest they have been since 1912, and there were 47 days classed as zero on the International scale.

Preparations for participation in the Polar-Year work delayed the publication of the Agincourt and Meanook results, but this work is now being rushed and it is hoped to bring it up to date this year.

Meteorological Service of Canada,
Toronto, Canada

MAGNETIC WORK OF THE DOMINION OBSERVATORY, CANADA

R. Meldrum Stewart

A systematic magnetic survey of the whole of the Dominion was the objective of those responsible for the inauguration of magnetic work by the Dominion Observatory in 1907. The point has now been reached in the development of the survey where, owing to the limited personnel available, little can be done beyond reoccupying repeat-stations for secular change, though a considerable part of the country has not yet been included in the general survey.

As reported in 1931, a program of observations at repeat-stations was begun in 1930. This was continued in 1931, and during the season observations of the three magnetic elements, declination, inclination, and horizontal intensity, were made at 35 stations representing 34 localities. In the region between longitude 60° west and 75° west, and south of latitude 49°, 23 stations were occupied. Of those remaining, which are in western Canada, nine are along the water-route to the Arctic Ocean between Chipewyan on Lake Athabaska and Arctic Red River on Mackenzie River. With the exception of two new stations, which were occupied at the time of the total solar eclipse in August, no field-work was done in 1932 owing to lack of funds.

Dominion Observatory,
Ottawa, Canada

MAGNETIC WORK OF THE NATIONAL ASTRONOMICAL OBSERVATORY OF MEXICO

Rosendo O. Sandoval

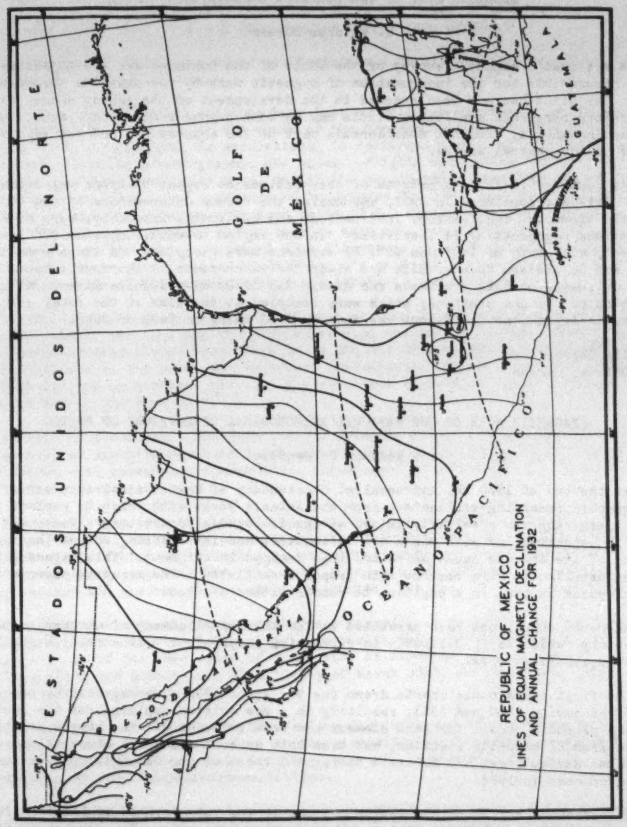
At the end of 1930 the Astronomical Observatory of Mexico acquired a set of photographic recording-variometers from the Askania Werke with which to replace the Mascart magnetograph previously in use at the Teoloyucan Observatory. Some time was spent in experimenting with these new variometers and in replacing one of the magnets and one of the Bourdon tubes which had been damaged in shipment. This magnetograph is now installed to give records with proper sensitivity. The magnetic observatory at Teoloyúcan is thus in a position to render better service.

Economic conditions have prevented so far the establishment of another magnetic observatory, which is so desirable in furthering geophysical work already begun in Mexico in its large area.

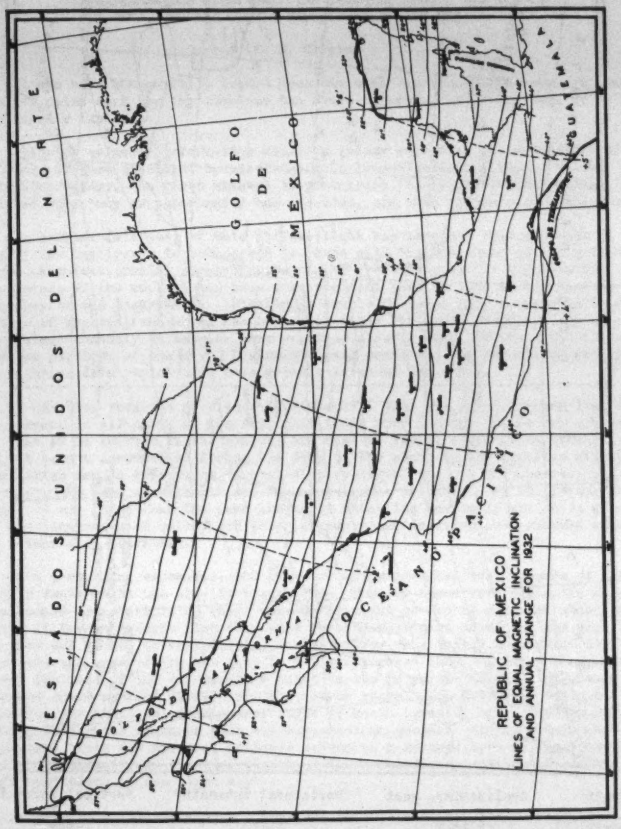
The first isomagnetic charts drawn for the epoch 1930 were improved by new observations during 1930 and 1931, resulting in a new edition applying for the epoch 1932 and of which copies for each element are here reproduced. The charts are based on data from 81 magnetic stations, and take into account also some observations of the United States Coast and Geodetic Survey and those of the Carnegie Institution of Washington made in 1924.

Attention is called to the isogonic lines in the neighborhood of Lower California; these show a great deflection in a northwestern direction along the coast of the Gulf of California, which changes to a southeastern direction on the Pacific side. These disturbances were noted also in reports of the United States Coast and Geodetic Survey for the years 1888, 1889, and 1896.

The accumulated data for these charts, published in Bulletins 12, 13, and 14, second series, of the National Astronomical Observatory of Tacubaya, furnish material for the study of secular variation. In Bulletin 12 the attempt is made to determine secular variation for Teoloyúcan. The equations deduced for this variation indicated a maximum in 1926, but actual observations later showed that the mathematical expressions were very far from the truth. Thus, we find ourselves in agreement with the recent statement of Daniel L. Hazard (see Terr. Mag., v. 37, 234, 1932), in which he says "With the accumulation of more accurate results for identical stations at shorter intervals, it became evident that no simple empirical formula would give a satisfactory representation of the observed changes..."

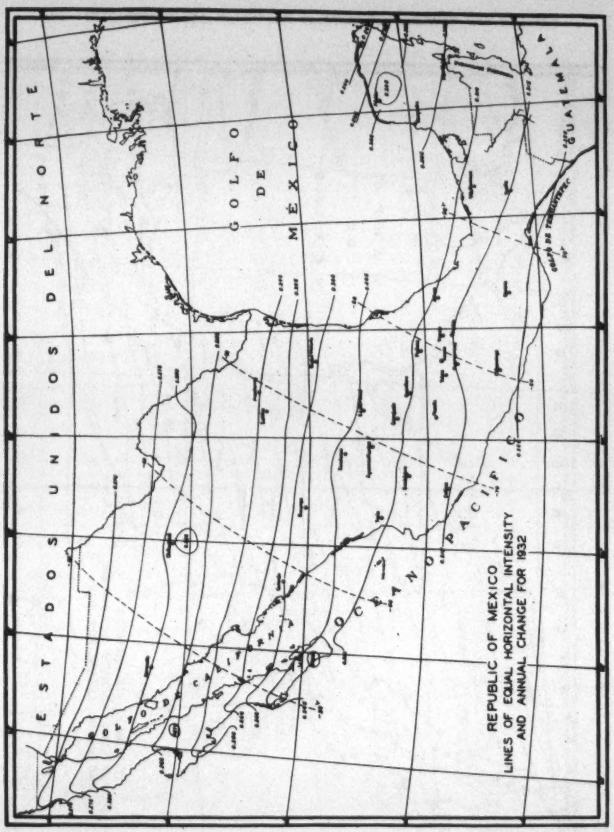


The writer is now investigating secular variation in relation to solar activity, and it is expected that the results will be published in a few months. Reference is made to a wave noted as appearing in the magnetograms. During the period from 1904 this particular wave appeared 86 times during the day-hours (6^h to 17^h) and 768 times in the night-hours (18^h to 6^h), there being two small maxima at 7^h and 14^h and a very great maximum at 21^h (105° west meridian mean time). Magnetograms kindly supplied us by the observatories at Huancayo, La Quiaca, Tucson, and Watheroo showed the same wave, and it is thus not a local phenomenon. Its characteristics are that (a) it appears generally on calm days; (b) its time of duration varies from 15 minutes to 2 hours; (c) its magnitude is from 1' to 5' in declination and from 10γ to 80γ in horizontal intensity; and (d) in most cases it is simple, positive or negative, but sometimes it is a double curve or two or three successive waves. Attention of mag-



netic observatories is called to this phenomenon, since it seems to occur over the entire world and seems to have no relation to magnetic storms but a close relation with the corona.

The following tabulation gives the mean monthly values of the magnetic values at the Teoloyucan Observatory deduced from magnetograms and expressed on the basis of International Magnetic Standards, for the year 1932.



Month	Declination, east	Horizontal intensity	Vertical intensity
	° '	γ	γ
January	9 28.2	31123	33429
February	9 29.9	31127	33387
March	9 30.4	31134	33396
April	9 29.5	31113	33392
May	9 30.5	31089	33380
June	9 30.7	31083	33369
July	9 30.2	31108	33365
August	9 31.3	31101	33391
September	9 30.9	31131	33467
October	9 31.9	31089	33407
November	9 31.0	31081	33397
December	9 32.6	31048	33342
Year 1932	9 30.6	31102	33394

Seccion Magnética, Observatorio Astronómico Nacional de Mexico,
Mexico, D.F.

SPECTRA OF THE NIGHT SKY, THE ZODIACAL LIGHT, THE AURORA, AND THE COSMIC RADIATIONS OF THE SKY

V. M. Slipher

All who have thoughtfully looked upon the clear moonless night-sky are aware that it is not quite dark but that, besides the stars, planets, and Milky Way, it is everywhere faintly luminous.

Believing valuable information would be gained regarding the nature and origin of this weak, diffuse sky-light by spectrographic investigation, I made, in 1915, at the Lowell Observatory, the first attempt to photograph its spectrum. Since then I have continued the study as opportunity has afforded, and with rather remarkable results.

The extreme faintness of this diffuse light has been the real obstacle to the study of its spectrum. To photograph it, even with the speediest plates and long exposures, requires special spectrographs of the greatest possible light-power. During the progress of the work it has been possible from time to time to increase much the efficiency of the instruments. Finally, a couple of years ago, I was able to design a new type of spectrograph which has been especially efficient because it is able to record simultaneously as many as five spectra, side by side, of the light of as many different portions of the sky. During the past year, two instruments of this type have gathered data rapidly and have greatly advanced the study.

It has been observed at Flagstaff since 1915 that the chief auroral line is always present in all parts of the sky, that it is more intense in the sky nearest the Sun, that it is weakest in the zenith, and that it varies somewhat in intensity; however, it is not accompanied during the dark of the night by the negative nitrogen-bands, which are so typical of auroral-display light, and yet the observations showed it to have the same wave-length and same appearance in the sky as in the auroral displays. It was found that the wave-length of this line was fully six units greater than the long-accepted value, and this large correction stimulated renewed study of this interesting radiation.

Then next, long exposures--100 hours or more--revealed the presence of a number of other features in the sky-light spectrum. Some of these were evidently emissions; others could be emissions or their appearance might be due to adjacent absorptions. In time it became evident that they were for the most part emissions and also that they were not of the auroral-display series. They were spread throughout the blue and violet and one interesting one also in the yellow near 5900. I first thought these strange features of the sky-spectrum might be due to very distant faint stars whose light and spectra might differ from the nearer stars. But this view could not be substantiated for there was no blend of light of known types of stars that would yield a spectrum having the features that the sky-spectrum showed. And it became more and more patent that these new spectral features belong to a strange type of spectrum that is peculiar to the diffuse light of the sky. These emissions I shall refer to as the cosmic radiations of the night sky.

During the brilliant aurora of May 14, 1921, I photographed a bright red line or band near λ6315, and in long-exposed spectra of the night sky I found the new yellow line near λ5900 was repeatedly recorded. Both these radiations, one auroral and the other sky, were seen to be fairly intense lines. It thus seemed very desirable to explore the red end of the sky-spectrum. The photographic obstacles I discounted by the thought that any emissions there would stand out clearer because of the low scattering-power of our air in the red. The extension of the study into the red promised to give additional information on the aurora and more still on the strange or cosmic radiations of the sky-spectrum. These efforts in the red were abundantly rewarded for new radiations were found there in surprising strength and numbers. Repeated plates continue to show these radiations and leave little doubt they are of a permanent nature, resembling the chief auroral line in the yellow λ5577. In order to get the spectrum, low dispersion is needed and this allows only approximate values of the wave-lengths. After a time, it was seen that these new radiations varied among themselves and in comparison with the yellow auroral line which years earlier had itself been found to vary.

At about the same time this study of the red spectrum was taken up, I found weak impressions of the typical auroral nitrogen-bands could be photographed in the morning and evening skies, if brief exposures were made at the critical moment when the first, or last, traces of sunlight touch the high atmosphere. These twilight auroral bands are commonly present and more intense in the sky toward the Sun. It may be repeated here that these auroral nitrogen-bands are never present during the dark of the night, except when an aurora is present.

Meanwhile I have also secured spectra of the zodiacal light and wish to digress a bit from the sky subject to touch upon this and the related phenomenon, the "Gegenschein." Recently new plates of these have been got with the multiple-image spectrograph. In this way it has been possible to photograph the spectra of the zodiacal light and Gegenschein under very favorable conditions, in that the spectra of regions of the sky removed from these subjects could be got simultaneously and brought alongside the studied spectra, making reliable comparisons possible. These new plates of the zodiacal light show a fairly strong background-spectrum of sunlight. Superposed upon this are, of course, the brightest of the night-sky cosmic radiations and also weak impressions of the negative nitrogen-bands typical of the spectra of aurorae. It is difficult to decide just how much of the strength of these nitrogen-bands is due to the zodiacal light since the twilight usually has these same bands. Further work using spectra made later at night and farther from the horizon may clear up this question. I am not able to decide from my Gegenschein spectra that the negative nitrogen-bands are present, but if so, they must be very faint. There also appears some doubt whether the continuous spectrum of the Gegenschein is slightly intensified by sunlight. Of course, the cosmic radiations of the night sky are superposed upon these Gegenschein spectra and they make it difficult to decide whether other very faint Gegenschein bands are also present.

Returning to the sky again, recently it has been possible to photograph the red sky-radiations with twilight-prism dispersion, and to improve the wave-lengths of some of them. It seems the radiation in the yellow falls very near the position of the sodium lines, whatever that may mean. The radiation near wave-length λ6315 (by earlier measures) is now clearly resolved into three lines. The middle, and much the strongest, is, by measurement, very close to wave-length λ6300, and the second strongest near wave-length λ6360, its weakness making it less accurately measurable. These two lines are by these measures well within expected agreement with the two forbidden lines of oxygen wave-length λ6300 and wave-length λ6363, intensities 4 and 1, which are related to the yellow auroral line of forbidden oxygen. In wave-length and in relative intensities the agreement seems quite satisfactory. Those red lines of greater wave-length are not yet well enough resolved and measured for identification.

Again, with the use of plates specially prepared and sensitive for the deep infra-red, I have recently discovered a new group of most remarkable sky-radiations. These are much more intense than those in the orange and red. Attempts to secure them with the 2-prism instruments have not yet met with success, and thus it is not now possible to give wave-length spectra of them of useful accuracy, nor is it possible to distinguish between lines and bands. There are seven or more of these, from wave-length 7200 to wave-length 8800, the strongest of these being near λ7400, λ7500, λ8250, λ8400, and λ8600. Of these the second and those at λ8250 and λ8600 are the most intense. While we must wait for more and better plates for useful wave-lengths and identifications, it tempts one to venture to point to the strong oxygen-lines in this region as likely to be involved in these brilliant new sky-radiations.

The remaining light of the sky, after deducting that coming from the stars and from the various types of auroral light, leaves an emission-spectrum of a great number of what we may call cosmic radiations as recorded in this study at the Lowell Observatory. These are distributed throughout the spectrum from the ultra-violet to the deep infra-red. These together must comprise the major fraction of the diffuse light of the night sky. This is especially true of the red and infra-red light, for there the scattered starlight is relatively very weak. Thus the early assumption that this faint diffuse night sky-light was due to stars must be considerably modified.

It has not been an easy matter to decide where the light giving these cosmic sky-radiations has its origin. With the new spectrograph, the spectra recorded of the four regions in the north, east, south, and west sky a little above the horizon and

another in the zenith, for comparison, show that these unidentified radiations are relatively stronger in the visual end of the spectrum for low regions of sky whereas for the zenith the violet of the spectrum is fully as strong as are the spectra of the low-altitude regions. Although we are doubtless dealing to some extent with general atmospheric absorption, which is most for the shorter wave-lengths, there is in my judgment another matter involved. This is the apparent strengthening of the longer sky-radiations with the increased air-path. It appears that this has more to do with the increased strength of the sky-radiations toward the longer wave-lengths than mere lack of absorptions appears to strengthen the shorter wave-lengths. In brief, this appears to make a fairly strong case that these unidentified cosmic radiations, for the most part, have their origins in the Earth's atmosphere. And we are led to believe the origin is some distance above the Earth's surface and that the layer of upper air involved may have quite appreciable thickness.

Tests have been made for altitude-effects at altitudes above and below that of the Lowell Observatory at Flagstaff. Its altitude is 7250 feet above the sea and tests were had at 10,500 and 3,000. The indications were that the sky-radiations were relatively to the spectrum-background more intense at the highest elevation. But the conditions were not the best especially for the tests at the lowest station, and it is desirable that these be repeated before considering that matter settled.

An attempt was also made in August 1932 to test the sky for these radiations during the total phase of the solar eclipse, but the results are hardly conclusive as the plates are too fully exposed to be able to show the type of radiations sought.

Further study of these radiations, especially those in the red and infra-red, where they are more intense relative to the blue, can not fail of valuable results, and the work is now in progress. While we can not in the time alloted us here follow this subject further, it is evident, I think, that we see our atmosphere taking on very remarkable optical rôles.

Lowell Observatory,
Flagstaff, Arizona

SOME RESULTS OF FURTHER STUDIES IN THE CORRELATION OF COSMIC PHENOMENA WITH RADIO INTENSITIES AS MEASURED AT THE PERKINS OBSERVATORY

Harlan T. Stetson

Researches in the investigation of the correlation of solar activity with radio reception have continued at the Perkins Observatory in the measurements of field-intensities of WBBM, Chicago, during the night hours from 9:00 p.m. to 2:00 a.m., Eastern Standard Time. Following the method of procedure outlined to the American Geophysical Union in 1932, the measurements have been corrected for the angle of depression of the Sun below the horizon after the correction-curve as was determined by Mr. Cobb.

Comparisons of radio intensities expressed logarithmically with the sunspot-numbers (see Fig. 1) confined to the central zones show a somewhat closer correspondence than when compared with sunspot-numbers for the whole disc, adding further evidence for an apparent direct sunspot-effect on the altitude of the Kennelly-Heaviside layer. The fact that the curve of radio intensities compares more closely with the sunspot-curve than with the curve of ultra-violet light, as determined from Pettit's measures at Mount Wilson, suggests that the increased ionization of the upper layers is effected by other considerations than the integrated ultra-violet light of the whole solar disc.

The investigation of a lunar effect upon radio from Perkins Observatory data has been continued. Josef Johnson has correlated the actual luni-tidal force at latitude 40° with the intensities of radio reception and finds evidence for points of inflection in the intensity-curve corresponding to critical values in the tidal force which presumably suggests critical layer-heights for optimum reception.

Further analysis of the data subsequently obtained during more than two years has

brought to light not only an apparent variation of field-intensities with the lunar hour-angle, but also with the lunar declination. Curves of Figure 2 show the values of field-intensities at lunar hour-angles 0 to 24, and for three cases, namely, (1) moon south at declinations -12° to -28°, (2) moon at the equator at declinations between -12° and +12°, and (3) moon north of the equator at declinations +12° to +28°. The fact that the two curves representing north and south declinations are inverted in phase is highly suggestive of tidal phenomena in the Kennelly-Heaviside layer. The curve representing field-intensities with the moon near the equator suggests semi-diurnal tides. A comparison of these curves with the curve of equilibrium-tides for latitude 40° (see Fig. 3) may be suggestive in arriving at some sort of explanation of a lunar effect upon the Kennelly-Heaviside layer. The fact that the tides at extreme declinations are diurnal, and that the semi-diurnal maxima occur for the case where the moon is near the equator, does not appear inconsistent with variations dependent upon latitude and the production of tides in an atmospheric ocean. It is difficult to explain the large variations here found on any simple gravitational tides in the atmosphere. A theory involving resonance may, however, be sufficiently elastic to offer some basis for explanation. Whether or not other sources of gravitational attraction enter into the problem involves further investigation.

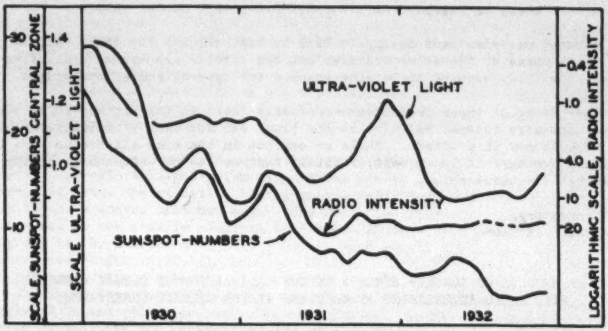


Fig. 1--Comparison radio intensities, sunspot-numbers, and ultra-violet light

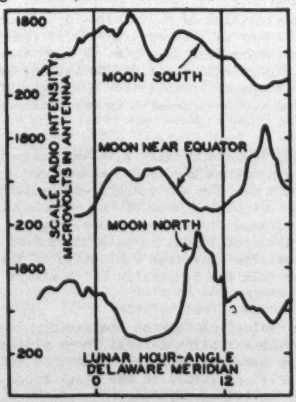


Fig. 2--WBBM radio intensity at Delaware and lunar hour-angle

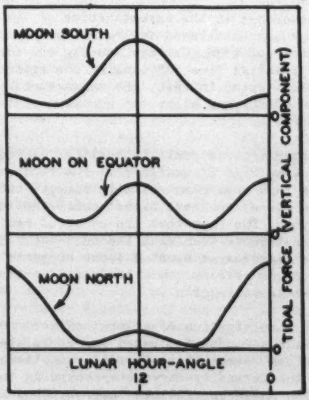


Fig. 3--Theoretical semi-diurnal tides, latitude 40°

The fact that the newer observational data include radio-intensity measurements distributed between 9 p.m. and 2 a.m., and therefore involving large changes in the lunar hour-angle in a single evening, should go far towards eliminating uncertainty as to whether or not the period of solar rotation confuses the correlation with lunar positions. It is felt that in the present instance the solar-rotation factor has been largely eliminated and that the present investigation offers considerable corroborative evidence for the lunar effect previously reported (Terr. Mag., v. 36, 1-6, 1931; also Perkins Observatory Misc. Sci. Papers, No. 8).

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THE INTERPRETATION OF THE RESISTIVITY PROSPECTING-METHOD FOR HORIZONTAL STRUCTURES

L. B. Slichter

(Abstract)

In almost all the problems of potential theory, the physical constants of material which enter are considered to be known functions of the position-coordinates; the solution of the problem is the potential function which satisfies the partial differential equation involved, and the prescribed boundary-conditions. The present problem is unusual in that the function to be solved is the one which expresses the unknown variation of the constant of material with position, whereas the potential function itself is considered to be known on the boundary. The problem is one which arises in the application of the resistivity-method to the investigation of geological structures. In Part I of this paper, the direct problem of interpreting the surface-potentials due to a point-electrode supplying current to the surface of a horizontally uniform Earth is treated, using a method due to R. E. Langer. In Part II, the more usual inverse problem is solved for some selected classes of conductivity functions, and graphical examples are given as an aid in guiding the interpretation work. In Part III, the anisotropic case is discussed.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

TRANSOCEANIC RADIO AND SOLAR ACTIVITY

W. A. R. Brown

For several years, the National Broadcasting Company has been engaged in a cooperative investigation of the effectiveness of long-distance, high-frequency transmission-circuits for international program distribution. Among the desired objectives were determination of the major solar and terrestrial phenomena which affect short-wave propagation adversely, their correlation with transmission and the practicability of forecasting these disturbances. It was believed that if these aims could be achieved in reasonable measure, international broadcasting would be placed upon a more practical operating basis and program-exchanges could be scheduled with a minimum of cancellations caused by failure of radio transmission-circuits. A summary of the methods employed and the results obtained are presented in the belief that the information may prove of value to others engaged in the investigation of the phenomena involved.

Systematic observations were made upon reception of various international relay-broadcast services operating on approximately 6, 9.5, 11.7, 15.1, 17.8, and 21.5 megacycles. Transatlantic circuits were observed several hours daily and Pacific and South American circuits less frequently. Reception was judged upon an overall basis, in contrast to usual practice, and was assigned a numerical rating to indicate its comparative value to program-quality obtained directly from a studio. These overall ratings, together with ratings of those factors such as signal-strength, fading, noise, etc., which determine the program-value of a signal, were entered graphically on the reception-log, so that transmission characteristics were evident at a glance. A typical log is shown in Figure 1.

PLT.-16-1M-2-29

RADIO RECEPTION RECORD

SHEET 279 A

PLANT OPERATION AND ENGINEERING DEPT.
NATIONAL BROADCASTING CO. INC.

OBSERVER E.F Bond WEATHER Clear Cold DATE Dec 24 1929

RECEPTION AT Riverhead, L. I.

SINGLE FREQUENCY RECEPTION

STATION G.S.S.W Chelmsford, England WAVELENGTH 25.53 M FREQUENCY 11,750 K.C.

MULTIPLE FREQUENCY RECEPTION – COMBINED OUTPUT

STATIONS	WAVE	FREQ.	NUMBER & DESCRIPTION RECEIVERS EACH FREQ.

TIME: LOCAL STD. ☒ E.S.T. GMT ☐ AM

RADIO RECEPTION CONDITION — SIGNAL STRENGTH: VERY GOOD; GOOD; FAIRLY GOOD; WEAK; JUST AUDIBLE — QRM: NONE; LIGHT; HEAVY — QRN: NONE; MODERATE; BAD — FADING: AMT.: LOW; MOD.; HIGH; FREQ: HIGH 1/2"; MOD. 1"; RAPID 10"

CHARACTER OF AUDIO SIGNAL — QUALITY: EXCELLENT; GOOD; FAIR; POOR; VERY POOR — NOISE LEVEL: FAIRLY LOW -45 db; MODERATE -30 db; HIGH 0 db; VERY HIGH +10 db — % OVERALL FOR REQ'D STRENGTH: EXCELLENT 80-100%; GOOD 60-80%; SATISFACTORY 40-60%; FAIR 20-40%; POOR 5-20%; VERY POOR 0-5%

REMARKS

NUMBER OF RECEIVERS USED THIS FREQUENCY 2

TYPE T.R.F

TYPE OF ANTENNAE Wave.

TIME	
7:30	
40	
50	
8:00	
10	Carrier off 8:08 AM.
20	
30	8:30 Discontinued.
PM	
2:00	2:00 PM - Wx - Cloudy - Cool
10	Note - modulation lower than on GSW announcement.
20	Unidentified QRM.
30	
40	
50	2:50 Normal Modulation.
3:00	Light audio fading starting
10	No audio fading now
20	
30	Intermittent light audio fading.
40	
50	
4:00	
10	No intermittent fluttering now.
20	
30	
40	
50	
5:00	Unidentified QRM.
10	Sig. Fluttering now
20	16 KW QRM from same ship.
30	
40	
50	
6:00	
10	
20	
40	
60	
7:00	

Fig. 1--Reception-log

Of the various relationships investigated, including solar, lunar, planetary, barometric, temperature, and magnetic, only the last showed any promise of day-by-day correlation. A sensitive index of terrestrial-magnetic activity was essential if the effects of magnetic disturbances upon transmission were to be isolated and the normal diurnal and seasonal transmission-variations determined. Although it is convenient to speak of the effects of a magnetic disturbance, it should be recognized that transmission-irregularities are probably due largely to abnormal ionization-conditions of the upper atmosphere, presumably caused by solar activity, and that these magnetic disturbances may be regarded as an indirect measure of such activity.

The magnetic index finally adopted was the daily sum of the hourly ranges of the horizontal component or, in some instances, the horizontal and vertical components together. These summation-ranges are easily and quickly obtained directly from the magnetograms and are vastly superior to magnetic character-figures or daily ranges. Even minor disturbances are readily detected. Daily summation-ranges for 1930 are shown in Figure 2. For practical reasons the magnetograms were obtained from the Tucson Observatory of the United States Coast and Geodetic Survey.

Although this Observatory is considerably south of the transatlantic circuit-paths, the magnetic index displayed a very satisfactory measure of correlation with transmission. Circuits traversing the high latitudes close to the auroral zone showed the highest correlation and apparently transmission-characteristics on these circuits are very closely related to the degree of magnetic activity existing at the time. Low-latitude circuits showed the least correlation because these appear to be comparatively immune to the effects of magnetic disturbances. On a number of occasions when the northern signals were badly affected, transmission on southern circuits remained practically normal, even over the long path between Australia and New York. Most of the transmission-irregularities on these low-latitude circuits, however, could be identified with magnetic disturbances. It is evident, therefore, that the degree to which transmission is disturbed is dependent upon the magnetic latitude traversed by the signal. While the actual explanation is not readily apparent, it is probable that the geographical variation in intensity of magnetic disturbances is an important factor.

The dependence of transmission upon magnetic activity is evident in Figure 3 which shows the weekly average overall reception-ratings of G5SW Chelmsford, England, during 1930, together with the amount of reception suitable for rebroadcasting. Normal diurnal reception-limits were obtained by averaging the overall ratings for the ten days per month on which magnetic activity was lowest. Figure 4 is a typical example of the 1931 reception-limits so obtained for I2RO, Rome, Italy.

The effects of magnetic disturbances upon short-wave transmission usually became apparent on the high-latitude circuits within a few hours after the commencement of the disturbance and were evident as changes in transmission-characteristics. Generally these changes could be placed in one or more of the following classifications: (1) An advance in the normal daily trend of transmission which at times resulted in night transmission-conditions existing during the day; (2) increased fading which at the maximum produced a signal equivalent to one modulated with a low audio-frequency; and (3) increased attention which caused premature fade-outs of the signals and occasionally resulted in the disappearance of signals for days.

These effects were more or less progressive in the order indicated, depending upon the intensity of the disturbance and the rapidity with which it built up, and were usually first apparent on the higher frequencies. With decreasing latitude, there was a progressive delay in the initial appearance of these effects and their magnitude. For storms of very high intensity, however, even the low-latitude circuits were eventually affected, particularly on the higher frequencies. The transition from one phase to another was frequently very rapid on northern circuits during severe storms and the entire cycle was often accomplished within a few hours. It is interesting to note that on these occasions the trend-advance phase sometimes merged directly into the attenuation-phase, which was then completed in a few minutes, and the signal was often exceptionally strong prior to the fade-out, with very little or no fading, despite the pronounced magnetic disturbance existing.

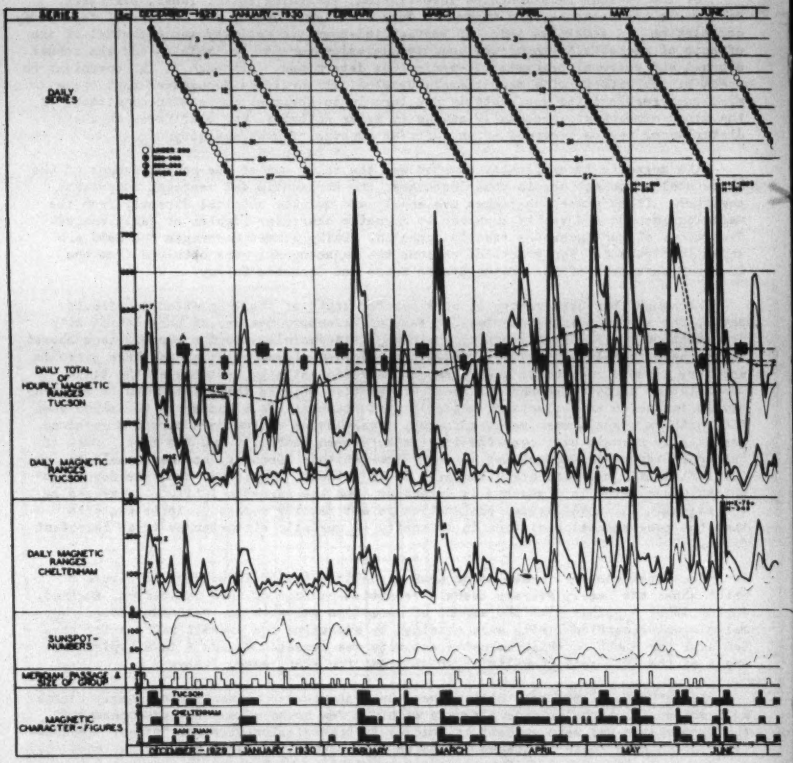

Fig. 2--Summation and daily ranges, 1930

The trend-advance consisted of a premature build-up of the signals. This action progressed across the short-wave spectrum from the high to the low frequencies until the second and third phases became effective. As a result, transmission often showed a substantial improvement during minor disturbances and the early stages of a storm. In general the effect was to shift the optimum wave-length to higher values. The appearance of the trend-advance was almost invariably a positive indication of increased magnetic activity and, conversely, one of the most pronounced effects of unusually quiet magnetic conditions was the extension of the normal useful period.

Frequencies close to the limiting value were in general most susceptible to magnetic disturbances, so that transmission appeared to be more easily affected in winter than in summer. The intensity and duration of disturbances frequently attained considerable magnitude in summer before the short-wave signals showed any detrimental effects. This was particularly true for disturbances in which the horizontal component fluctuated rapidly and widely about a mean value which was not greatly below the normal average.

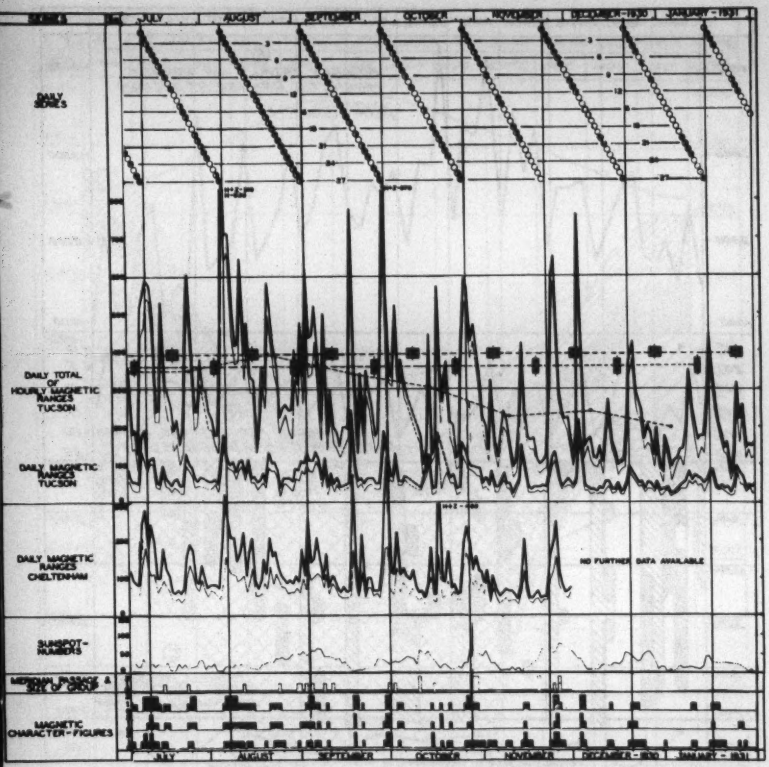

Fig. 2--Summation and daily ranges, 1930--Concluded

Recovery of signals after a magnetic storm does not follow a reversal of the three phases previously mentioned. Fading usually returned to normal values before the signal-strength, indicating that the turbulence of the upper atmosphere disappears before the excessive ionization.

The extensive storms which extend over a period of a week or so appear to be composed of several individual disturbances closely following one another and it is possible in some instances to trace the independent build-up and decay of the individual storms on successive recurrences. This suggests that these storms are due to separate "active solar areas" rather than intermittent emissions from one area.

Although magnetic disturbances and transmission-irregularities are presumably due to the action of solar agencies, no day-by-day or short-period correlation appears to exist between either of these and the various indices of solar activity, such as sunspots, faculae, or flocculi. This is illustrated in Figure 5 which shows moving three-day averages of magnetic activity and the solar character-figures for 1930.

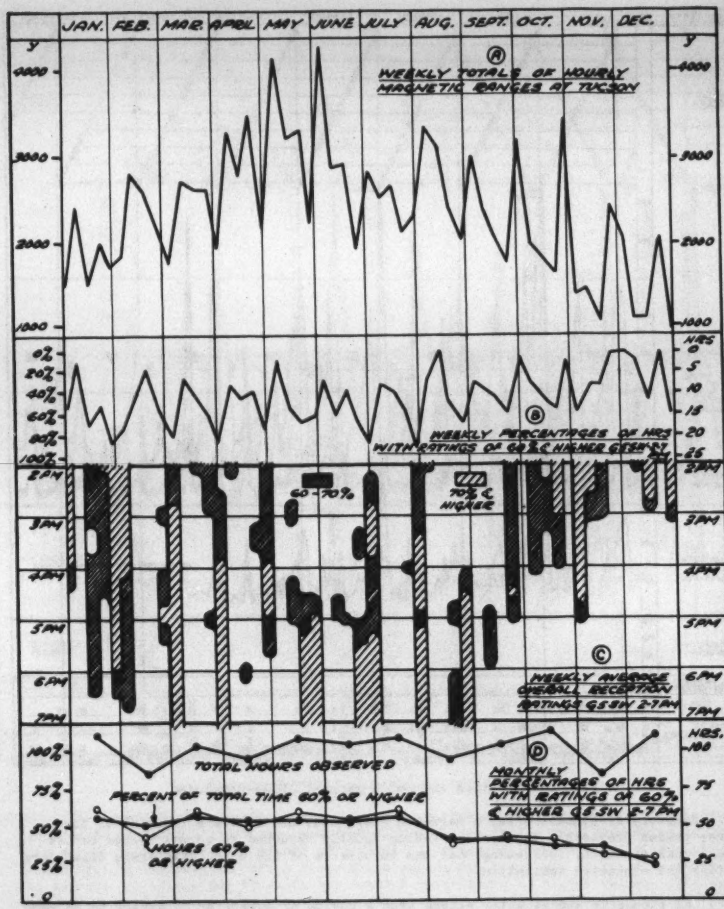

Fig. 3--Magnetic activity and reception of G5SW Chelmsford, England, 11750 kc, 1930

A very interesting long-term correlation has been apparent, however, in the progressively yearly shift to lower optimum frequencies since the last sunspot-maximum. This has resulted in a pronounced contraction of the useful reception-period for the higher frequencies and some of these, particularly at the upper end of the spectrum, which a few years ago provided good reception, are now of little value. Conversely, the utility of the lower frequencies has increased greatly due to expansion of the useful period and decreased attenuation. Here again, these effects are most pronounced on high-latitude circuits. This phenomenon is similar to the diurnal variation of transmission, except that in this case the period corresponds to the length of the

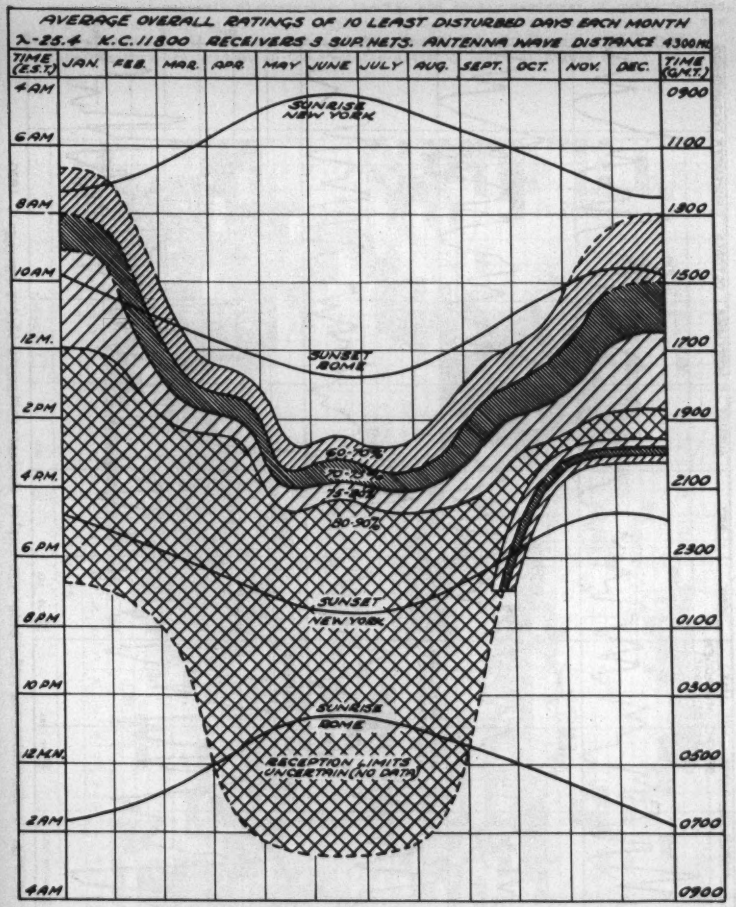

Fig. 4--Reception of I2RO Rome, Italy, at Riverhead, N.Y., 1931

sunspot-cycle, with day transmission-conditions during the sunspot-maximum and night conditions at the sunspot-minimum.

In the prediction of day-to-day transmission-conditions, which is obviously highly desirable, sufficient accuracy has been attained to warrant its inclusion as an operations function. Such forecasting is dependent upon the prediction of magnetic activity. We admit that this is merely intelligent guessing, based upon certain characteristics of magnetic activity together with the experience gained from observation of this phenomenon over the past five years. These characteristics are the 27-day

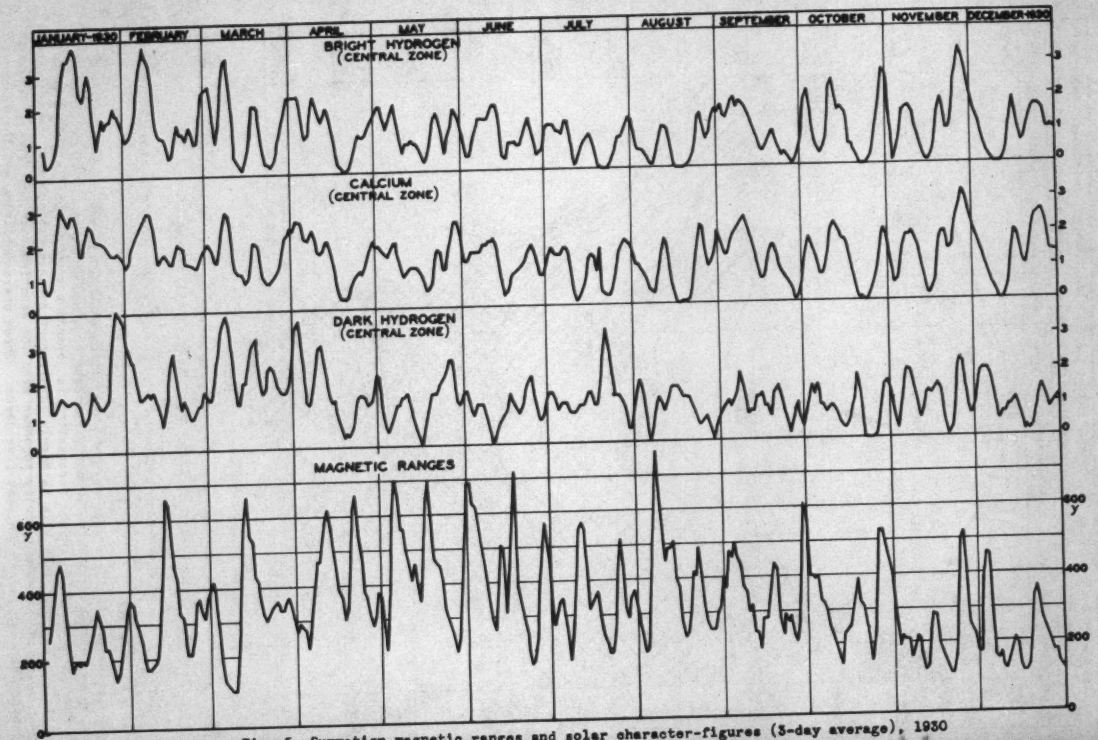

Fig. 5--Summation magnetic ranges and solar character-figures (3-day average), 1930

recurrence of magnetic disturbances, the 26- and 28-day sequences of quiet periods, the cycle of build-up and decay displayed on successive storm-recurrences, and the general confinement of disturbances to the period between the solstitial dates. These factors are evident in the magnetic-activity chart of Figure 6.

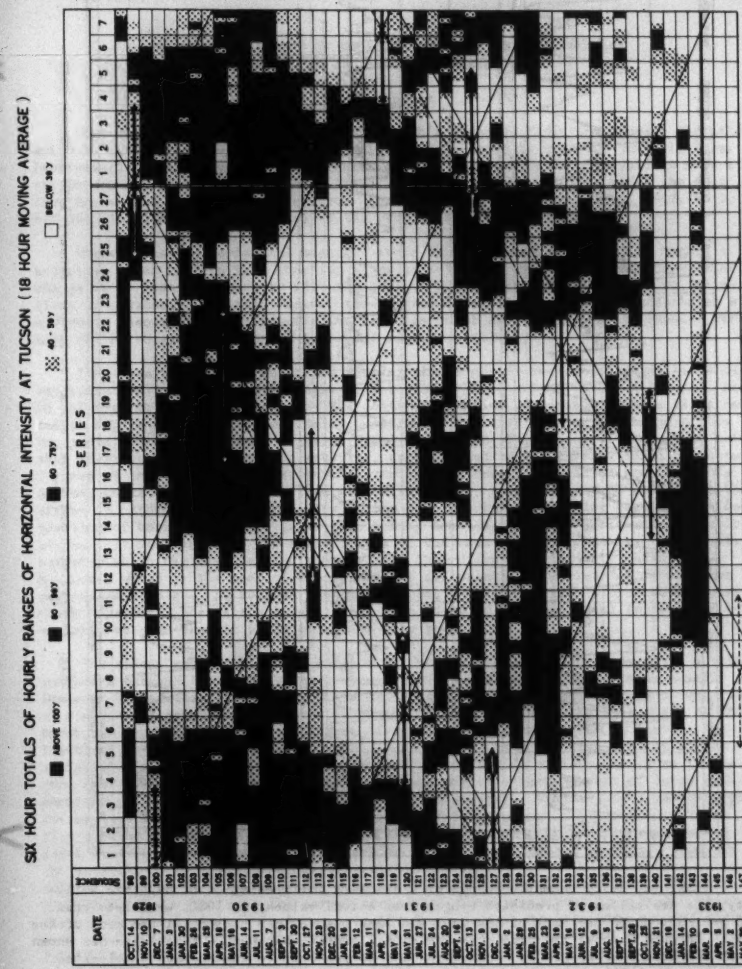

Fig. 6--Magnetic activity at Tucson, October 1929-April 1933

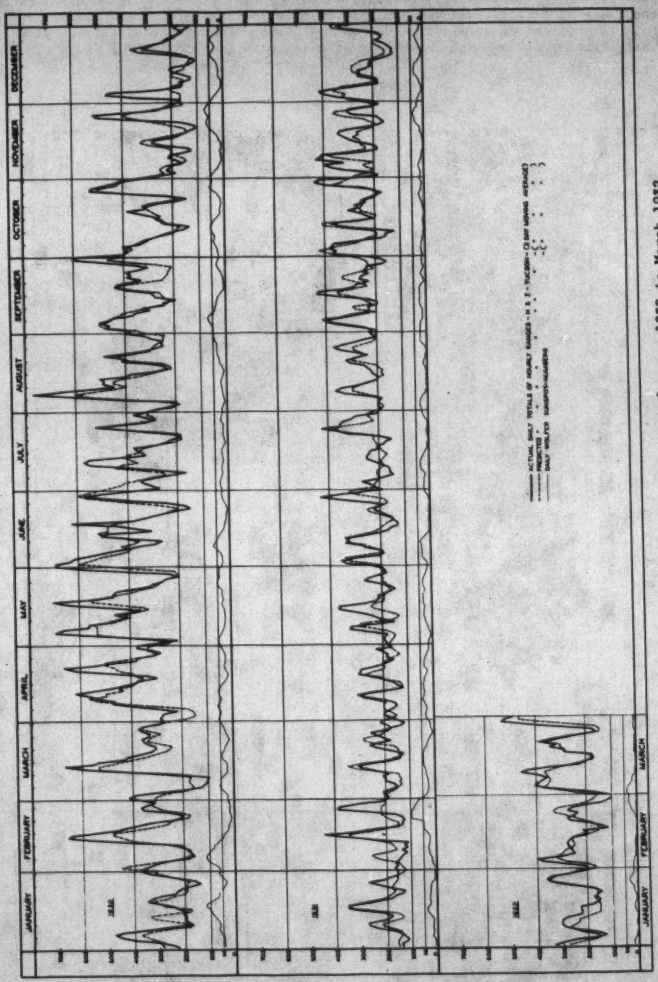

Fig. 7--Predicted and actual summation-ranges, January 1930 to March 1932

Using the daily summation-range as a standard for prediction of magnetic activity, the deviations of predicted ranges from actual values, in 1930, were less than 20 per cent on 53 per cent of the days and less than 30 per cent on 71 per cent of the days. Figure 7 shows the predicted and actual summation-ranges. Experience has shown that deviations of 25 per cent in winter and 50 per cent in summer may be tolerated before predicted transmission-conditions, on most frequencies, are materially altered.

Acknowledgment is made of the reception-reports furnished by the RCA-Communications, Inc., the General Electric Company, the Westinghouse Electric and Manufacturing Company, the British Broadcasting Corporation of England, Philips Radio of Holland, and the Reichs-Rundfunk-Gesellschaft of Germany and also of the courtesies extended the National Broadcasting Company by the United States Coast and Geodetic Survey.

National Broadcasting Company,
New York, N. Y.

THE APPARENT EFFECT OF MAGNETIC ACTIVITY UPON THE SECULAR VARIATION OF THE EARTH'S MAGNETIC FIELD

A. G. McNish

That the horizontal component of the Earth's magnetic field undergoes a variation which is associated with the sunspot-cycle has been noted by numerous investigators. Particularly noteworthy is the monumental work of Moos (Magnetic observations made at the Government Observatory, Bombay, 1846-1905, Part 2, 265, 1910) in which the data from Bombay are discussed. Fisk (Proc. Fourth Pacific Sci. Cong., Java, 1929, v. 2, 517-534, 1930) has also investigated the problem in another way.

However, as the horizontal magnetic force is considerably affected by magnetic activity, which in turn is a function of solar activity, correlations of the secular change in horizontal intensity with the sunspot-numbers are likely to lead to fallacious conclusions. For this reason, the present investigation has been undertaken with a view to discovering more exactly the relation which exists between the secular variation of the horizontal magnetic force and magnetic activity.

There are two ways in which the secular change of the horizontal magnetic force may conceivably be affected by magnetic activity. The first of these, which will here be referred to as hypothesis A, is the post-perturbation phenomenon. It is illustrated in Figure 1--a diagram originally prepared by Bartels--showing the trend of the horizontal force for 37 days at three widely separated observatories. It may be noted that at times of great magnetic activity, as indicated by the international character-figures at the bottom, the horizontal force is considerably depressed and that this depression is greatest for stations in low latitudes. Also, it may be noted that the effect is rather ephemeral, recovery to the predisturbed value being rapid. This depression of horizontal force is an outstanding characteristic of world-wide magnetic storms. It has served as the basis of one of the most reliable measures of magnetic activity which has been devised, namely, the interdiurnal-variability measure (u-measure), which is the mean of the day-to-day differences of horizontal force taken regardless of sign. It follows then that during a year when many storms have occurred these depressed intervals will cause the mean value of the horizontal force to be lower for that year than it would otherwise have been.

The second way in which the horizontal force may be affected by magnetic activity considers whether the force, after recovering from the depression, attains a value lower or higher than it had before the depression. The principal feature of the field of a magnetic storm is illustrated in Figure 2. The permanent magnetic field of the Earth, as shown in diagram A of Figure 2, reproduced from a diagram by Bartels, is identical to a first approximation with the field due to a magnetic doublet at the center of the Earth. The field due to a world-wide magnetic storm, as shown in diagram B of Figure 2, is identical with the field due to a ring-current of large radius encircling the Earth in the plane of the Earth's equator. Contrary to a rather popular notion, the effect of a magnetic storm is to temporarily increase the magnetic flux passing through the Earth, although the horizontal magnetic force exterior to the Earth is everywhere reduced within a region close to the Earth's surface. Thus, by the establishment of electric currents within the Earth, or by increasing the intensity of magnetization of the Earth's material, it might be expected that after the disturbing field dies away the normal horizontal force would rise to a higher value than it previously had, like Antaeus in the Greek legend who rose with renewed vigor each time he was struck to the ground. This hypothesis was advanced by Chapman (Mon. Not. R. Astr. Soc., v. 79, 75, 1918) and will here be referred to as hypothesis B. So pregnant does the idea appear that, if it may be substantiated, enticing theories of the origin of the Earth's permanent field loom upon the horizon.

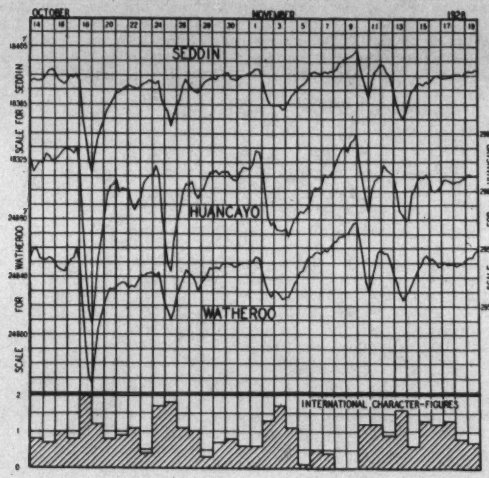

Fig. 1--The world-wide nature of post-perturbation indicated by similarity of three curves showing the daily means of magnetic north component at Seddin (Germany) and horizontal intensity at Huancayo (Peru) and Watheroo (Western Australia), Oct. 14 to Nov. 19, 1928 (Plotted means for consecutive 24-hour periods, 6 hours apart; those for 24 hours centered at Greenwich midnight coincide with vertical lines)

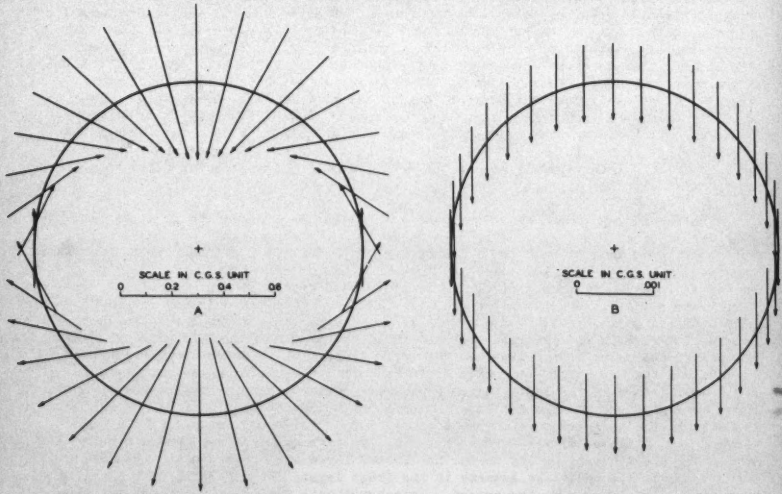

Fig. 2--Cross-section of Earth's permanent magnetic field (A) and of field of world-wide magnetic storm (B)--storm-field increases flux within Earth

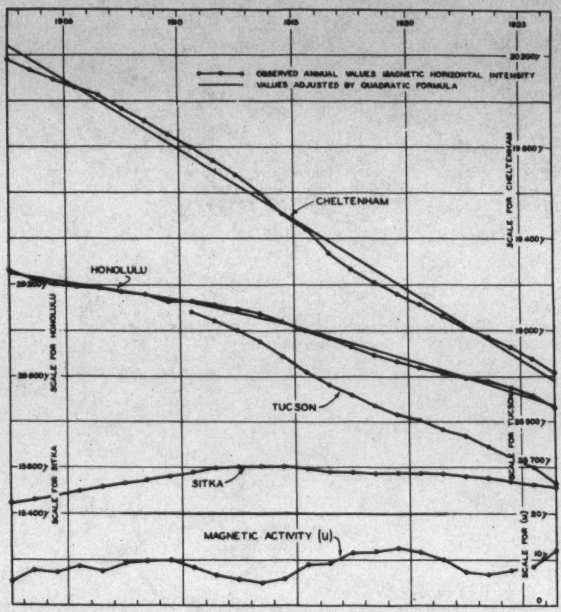

Fig. 3--Comparison annual values magnetic horizontal intensity for all days with magnetic activity (u) as determined from interdiurnal variability in horizontal intensity at many observatories

A casual examination of Figure 3 discloses that while magnetic activity is a cyclic phenomenon, the secular change of the horizontal magnetic force exhibits a trend, different for different observatories, which quite overshadows the cyclic portion. A direct correlation of annual values of horizontal force and magnetic activity would reveal nothing when taken over any considerable interval. By taking differences, however, all but the periodic portions are eliminated, as shown by the equations (1) to (6) which follow:

$$(1)\quad H = K + At + Bt^2 + \Sigma C_i \sin(2\pi t/T_i + \varphi_i)$$

$$(2)\quad \Delta H = K' + 2B\Delta t\, t + \Sigma 2C_i \sin(\pi\Delta t/T_i)\cos(2\pi t/T_i + \varphi_i + \pi\Delta t/T_i)$$

$$(3)\quad \Delta_2 H = K'' - \Sigma 4C_i \sin^2(\pi\Delta t/T_i)\sin(2\pi t/T_i + \varphi_i + 2\pi\Delta t/T_i)$$

$$(4)\quad u = k + \Sigma c_i \sin(2\pi t/T_i + \theta_i)$$

$$(5)\quad \Delta u = + \Sigma 2c_i \sin(\pi\Delta t/T_i)\cos(2\pi t/T_i + \theta_i + \pi\Delta t/T_i)$$

$$(6)\quad \Delta_2 u = - \Sigma 4c_i \sin^2(\pi\Delta t/T_i)\sin(2\pi t/T_i + \theta_i + 2\pi\Delta t/T_i)$$

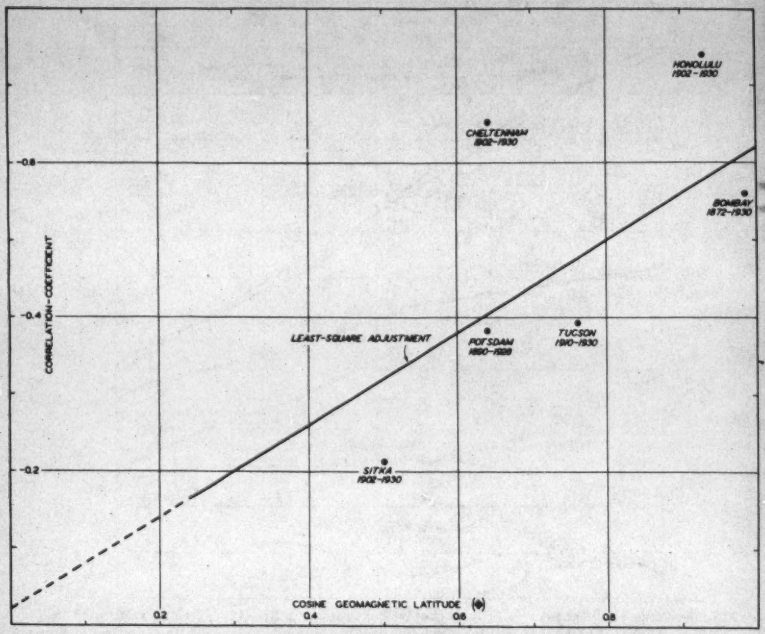

Fig. 4--Correlation-coefficient between second differences annual values magnetic horizontal intensity and magnetic activity as a function of geomagnetic latitude

The mean annual values of the horizontal magnetic force at any observatory over any interval of time may be accurately represented by equation (1). Similarly, magnetic activity may be represented by equation (4). No restrictions are placed upon the values which T_i, C_i, c_i, φ_i, and θ_i may assume, nor, for the purposes of this discussion, is it necessary that the same periodicities continue throughout the interval. However, in so far as the cyclic portion of H is caused by u acting as described in hypothesis A, the periodic terms in equations (1) and (4) will be identical. As the quadratic portion of (1) is, for most observatories, much greater than the cyclic portion, an appreciable correlation between corresponding values of H and u is not to be expected. On the other hand, the second differences, given by (3) and (6), contain no non-periodic variables and, if hypothesis A is the explanation of the cyclic tendencies of H, a negative correlation is to be expected between $\Delta_2 H$ and $\Delta_2 u$, implying that all values of C_i and c_i are proportional and that the values of φ_i and θ_i differ by 180°.

If hypothesis B is the explanation of the cyclic portion of H, a positive correlation is to be expected between corresponding values of $\Delta_2 H$ and Δu given by equations (3) and (5), carrying with it implications analogous to those stated above. If both hypotheses are the explanation, perfect correlation cannot occur in either case and the relative magnitude of the two correlation-coefficients is a measure of the degree to which each hypothesis acts.

It must be remarked that in taking differences the amplitude of each periodic term is multiplied by $2 \sin (\pi \Delta t / T_i)$ so that higher-order terms appear in the differences with greater weight than those of lower order. The relative magnitude of these

amplification-factors for various periods is given in Table 1. The seriousness of this fault of the method of analysis is considerably mitigated by the facts that the amplitudes of the higher-order terms are slight and that, by taking annual means rather than point-values, the higher-order terms are somewhat smoothed out. This feature has the advantage, however, that by taking bi- or tri-annual differences the relative importance of various periodicities in the correlation can be ascertained.

Table 1--Relative amplification-factors of trigonometric terms in first and second differences; T, length of period, Δt length of time over which differences are taken

T/Δt	(Δt/T) × 180°	Amplification-factors	
		First differences	Second differences
24	7°.5	0.131	0.017
18	10.0	0.174	0.030
12	15.0	0.259	0.067
8	22.5	0.383	0.147
6	30.0	0.500	0.250
4	45.0	0.707	0.500
3	60.0	0.866	0.750
2	90.0	1.000	1.000
1.5	120.0	0.866	0.750
1.0	180.0	0.000	0.000

To investigate the two hypotheses, the data from the seven observatories shown in Table 2 were treated as described. The annual values for all days were used. No avail-

Table 2--Correlation-coefficients between differences of horizontal intensity and of interdiurnal-variability measure of magnetic activity from widely distributed observatories; A, second differences; B, second differences of horizontal intensity with first differences of magnetic activity

Observatory	Geomagnetic latitude, Φ	Dates	A	B
	°			
Bombay	9.5 N	1872-1930	-0.56	-0.11
Batavia	18.0 S	1884-1926	-0.30	+0.11
Honolulu	21.0 N	1902-1930	-0.74	+0.03
Tucson	40.4 N	1910-1930	-0.39	+0.17
Cheltenham	50.1 N	1902-1930	-0.65	+0.26
Potsdam-Seddin	52.5 N	1890-1928	-0.38	-0.06
Sitka	60.0 N	1902-1930	-0.21	-0.16

able data were rejected except the somewhat uncertain values from Bombay previous to 1872 and one pair of second differences from the Potsdam-Seddin series which seemed to be affected by a change in the method of tabulation. The u-measure of magnetic activity, previously described, was taken from a compilation by Bartels (Terr. Mag., v. 37, 11, 1932).

A pronounced negative correlation was found to exist between the second differences of the annual values of horizontal force at each observatory and the second differences of the annual values of magnetic activity as shown in column A of Table 2, strongly supporting hypothesis A. The coefficients are greatest for stations in low geomagnetic latitudes. The coefficient for Batavia is conspicuously low due, presumably, to the location of the observatory in the East-Indian region of secular-change anomaly. These correlation-coefficients, plotted against the geomagnetic latitude, are shown in Figure 4, Batavia, being omitted. A straight line fitted to the points by least-squares passes close to the origin of the coordinates indicating that no correlation is to be expected in very high latitudes, while a comparatively high negative coefficient is to be expected near the magnetic equator, confirming the indications of Figures 1 and 2.

The correlation-coefficients between the second differences of horizontal force and the first differences of magnetic activity are small and variable in sign, as shown

in column B of Table 2, indicating that the effect stated in hypothesis B is small or altogether non-existent.

It is to be concluded, therefore, that during years of high activity the horizontal magnetic force will be lower than during years of low activity, other factors being the same, although the activity occurring during a year will have little or no effect upon any change in the horizontal force which may occur during that year.

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THE PROBLEM OF VERTICAL EARTH-CURRENTS

O. H. Gish

That an electric current, which will be called the air-earth current flows from the air to the Earth, at all places where fair weather prevails is established beyond doubt by a mass of data regarding the potential gradient and conductivity of the air as well as by some more direct measurements. This current is far too small to appreciably influence the instruments which are used in measuring the components of the Earth's magnetic field.

The magnetic measurements, however, by suitable analyses give some evidence of vertical electric currents which in certain regions flow from air to Earth and in others in the reverse direction. These, which will be called magnetic-line-integral currents, are about 10,000 times the magnitude of the air-earth currents, and if real they produce no detectable effect upon the instruments which are used in measuring the electrical state of the atmosphere. Another class of vertical electrical currents is thought by some investigators to be indicated by measurements of the difference of potential between points at different depths in the Earth or at different levels on a mountainside. Thus it is found that, when two plates are placed in the Earth on a mountainside and connected by a wire stretched over the surface, a current nearly always flows in the wire from the point at the lower to that at the higher level. If such observations indicate currents in the Earth which everywhere flow "uphill" then the intensity of these vertical earth-currents (as they will be termed) are probably 10 or 100 times that of the magnetic-line-integral currents, and perhaps one million times that of the air-earth current. The fact that no counterpart of either the magnetic-line-integral currents or of the vertical earth-currents can be detected as a conduction-current in the atmosphere, leads to one or the other of two views, namely, either (a) they do not exist or else (b) they are manifestations of some as yet unknown physical principle or element.

Although the latter view has been suggested by some writers, it seems unsafe at the present stage of these investigations to yield to it. On the other view there is nothing to discuss except the reasons for entertaining that view. To this end it may be said that the evidence for the magnetic-line-integral currents appears to lie so near the margin of uncertainty that skepticism seems justified. A more complete investigation so made, if possible, as to bring out a measure of the uncertainty, should provide a satisfactory basis for a decision.

There is doubt whether a similar remark applies in the case of the vertical earth-currents. It seems rather that here the interpretation of the observed data may be at fault. This warning also applies to some other aspects of earth-currents. Curiously there seems to be a tendency for investigators of earth-currents to take one or the other of two extreme views. One of these views is illustrated by the definition of earth-currents, given in a well-known unabridged American dictionary. This runs as follows: "Earth-currents, light electric currents, apparently traversing the Earth's surface, but which in reality only exist in a wire grounded at both ends, due to small potential differences between the two points at which the wire is grounded." This definition is commended for the attitude of skepticism expressed--not for elegance of form or accuracy! Had every investigator of vertical earth-currents entertained this attitude at the outset of his work, there would perhaps exist no need for these comments.

The other extreme view is that of credulity. It takes for granted that a current flows between two points of the Earth, if measurement shows a difference of potential between the points. In the light of known facts, neither of these extreme views is tenable. That electric currents flow in the Earth at times could scarcely be doubted after 1847 when Barlow reported his observations on telegraph-lines in England. The evidence collected since then shows without doubt that such currents exist at all times. However, that which is measured (a current in a wire which connects two plates placed in the Earth, or the difference in potential between those plates) is not all contributed by the electric current in the Earth. Faraday in 1830 recognized that what he measured in a line connecting two plates suspended in the River Thames, did not necessarily imply that electric currents normally flow in the water. But today this is too often overlooked.

A false indication of current in the Earth may arise in a number of ways. As examples: If two electrodes, as much alike as is feasible to prepare them, are placed in pure water, they form an electric cell, the electromotive force of which will be quite small compared to that of a dry cell, but not generally negligible in measurements made in the study of earth-currents. If the pure water is replaced by earth, the circumstances are less favorable and hence electromotive forces one or two orders of magnitude larger may be expected. These contact-potentials may be reduced by using reversible, or so-called "non-polarizable," electrodes, instead of ordinary metal plates. A simple type of reversible electrode is made by suspending a copper plate in a concentrated solution of copper sulphate, which is held in a porous porcelain jar. The jar of course is imbedded in the earth. However, the attention which such electrodes require in order to realize an advantage from them is an important handicap.

Furthermore, there is another and often more important source of illusive results, namely, a difference in potential which exists wherever there is a concentration-gradient in an electrolyte. This may be illustrated by a laboratory experiment. A solution of a salt, say, zinc sulphate, held in a large porous jar is partially submerged in a body of pure water. If by using two electrodes (for example, a copper-in-copper-sulphate type) differences in potential are measured between points in this cell, it would be found that when both electrodes are in water or in zinc sulphate the measured values are much smaller than when one is in water and the other in the zinc-sulphate solution. Analogous circumstances frequently occur in the Earth. A wet spot of earth would generally be found to be at a different potential than the surrounding dry area. A clay bed surrounded by sand presents a similar condition. But a current does not flow in cases like these unless a third suitable conductor interconnects the two bodies of dissimilar earth. The fact that the boundaries in actual cases are not always sharp, but that the transition from one condition to the other is gradual, is of minor importance.

Perhaps the so-called vertical earth-currents are phenomena of the type illustrated by the foregoing examples. If so, then one or more constituents of the Earth's surface-material must be dependent upon elevation. Such a dependence may be attributed, in part or in whole, to several factors. The age, character, and genesis of a mountain, the intensity and duration of erosion or weathering, are some of the possible factors. These should be given consideration when formulating plans for the investigation of vertical earth-currents and when interpreting data.

Rather significant evidence on this matter is presented by measurements of "active acidity" made by botanists in the course of ecological studies in the United States (Stanley A. Cain, Botanical Gazette, v. 91, 22-41, 1931), England (E. J. Salisbury, J. Ecology, v. 9, 220-240, 1922), and Germany (Eugen Frank, Ueber Bodenasiditât im Walde, Freiberg, 1927; see also Biol. Abs., v. 3, 1440, 1929). These indicated that soil at higher levels is generally more acid than that at lower altitudes. The results reported by Cain indicate an average decrease in the hydrogen-ion coefficient of about 0.0038 per meter increase in altitude. Such a value may imply that a potential gradient of about 0.2 volt per kilometer would be measured if hydrogen-electrodes were used. In the calculation of this value it was assumed that the actual case is equivalent to a simple concentration-cell of two liquid phases at a temperature of 300° K and diffusion-potentials were neglected. The sign of the calculated gradient is opposite to that observed (contrary to previous statements by the author). This is, however, not vital. With other electrodes the opposite sign of the

apparent gradient may be obtained. It is doubted whether the sign can be predicted for the electrode-materials which have been used in the investigation of vertical earth-currents. One would expect, however, that properly controlled measurements with a variety of materials as electrodes, should present evidence as to whether vertical earth-currents are real or whether only apparent.

These observations of the hydrogen-ion concentration of soil, as a function of altitude, although by no means decisive, do lend considerable support to the view that a mountain peak, for example, may resemble a battery through which a current does not necessarily flow except when some external conductor is introduced. Various modifications of such a view are of course possible. Current may flow up the slopes and return down the axis of the mountain and thence back through deeper strata of earth to a pole at a lower elevation. But it is not the purpose here to elaborate an electrochemical theory of vertical earth-currents; instead it is hoped that stressing here the possibility of such an origin may enlist the consideration which such factors require before concluding that vertical earth-currents exist in contravention of fundamental physical principles.

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PROGRESS-REPORT ON THE INTERNATIONAL POLAR YEAR OF 1932-33

J. A. Fleming

The importance of securing increased knowledge of the physics of the Earth through observations in the inaccessible polar regions has long been recognized, but polar explorers and observers--because of limited means and lack of cooperative opportunities--have not always found it possible to undertake scientific programs simultaneously at many stations over even short periods. The polar records of pioneer and heroic endeavor give ample evidence of this. There was, however, one notable exception, namely, the First International Polar Year of August 1882 to August 1883 sponsored by the International Meteorological Organization following suggestions made in 1875 by Lieutenant Karl Weyprecht of Austria. That endeavor showed how highly profitable a simultaneous program for a full year at many stations may be, as is witnessed by the theoretical and practical applications of some 20 published volumes of its results.

The many new problems indicated by advances of the Earth sciences during the past 50 years requiring additional data for their solutions show clearly the desirability of obtaining another such series of observations. Again the International Meteorological Organization sponsored such an effort and at its Conference at Copenhagen (Proces-Verbaux des séances de la Conférence Internationale des Directeurs du Comité Météorologique International et de Diverses Commissions à Copenhague, Septembre 1929, Utrecht, Secretariat du Comité Météorologique International, No. 3, 1930) in September 1929, with representatives from 34 countries present, proposed a program for a second International Polar Year. While this plan is designated as a "polar year," it was recognized effective enhancement of geophysical research now requires distribution of special stations not only in polar regions but throughout the entire Earth. Thus further accumulations of data bearing on geophysical phenomena as evidenced in the arctic and antarctic must include similar data obtained simultaneously at many points in all parts of the globe and at certain strategically--in the geophysical sense--placed stations, particularly in tropical regions.

Details for the proposed program were developed carefully under the direction of a special International Polar Year Commission for 1932-33 of representative geophysicists appointed by the International Meteorological Organization. Dr. D. la Cour, Director of the Danish Meteorological Institute, is President of the Commission. The cooperation so generously extended on all sides again emphasizes the truly international character of science unhampered by national boundaries and aspirations. The transactions of the Commission's meetings and its reports so far published furnish ample evidence of the magnitude of the task and of the laborious character of necessary preparations and details. The first and second printed reports of the transactions of the meetings at Leningrad in August 1930 and at Innsbruck in September 1931 include the

history of the effort and its organizations, the resolutions adopted for guidance, and appendices giving details and recommendations for observation, for equipment, and for general plans for observatories and quarters. [See Premier rapport de la Commission Internationale de l'Année Polaire 1932-1933, Leyde, Secrétariat de l'Organisation Météorologique Internationale, No. 6, 1930; Procès-Verbaux des séances du Comité Météorologique International à Locarno Octobre 1931, et rapports de trois commissions et d'une sous-commission à Innsbruck et Locarno, Septembre et Octobre 1931 (Appendice H--Commission de l'Année Polaire 1932-1933, Procès-Verbaux des seances à Innsbruck, 23-26 Septembre 1931), Leyde, Secrétariat de l'Organisation Météorologique Internationale, No. 10, 1932--for copies of resolutions adopted, see Terr. Mag., v. 35, 245-248, 1930; v. 36, 319-332, 1931; v. 37, 185-186, 1932. For a summary of the status January 1, 1932, see J. A. Fleming, The proposed Second International Polar Year 1932-33, Geog. Rev., v. 22, 131-134, 1932.] Circular reports and letters dealing with detailed instructions for each field of observation, development of special instruments and equipment, method and style of publication, etc., have kept the plans and progress current. It is of interest that the Commission's attitude to prepare for the utmost profit and for the most economic use of the opportunities and funds is everywhere reflected throughout these--an attitude doubtless largely instrumental in effecting successful issue of those plans despite the present economic world difficulties.

The primary fields of investigation include meteorology, terrestrial magnetism, and terrestrial electricity, although many organizations are taking the opportunity to add other geophysical research. Under meteorology there are synoptic and term observations, as well as continuous registrations of pressure, temperature, humidity, wind-direction, wind-force, cloud-heights, cloud-photographs, condensation-nuclei, and radiation-measurements (intensity, absolute, and polarization), as well as exploration of the upper atmosphere by pilot-balloons, sounding-balloons, radiosondes, airplane-flights, and kite-flights. In terrestrial magnetism and electricity there are absolute measurements and registrations of the three magnetic elements (ordinary and quick-run time-scales); of atmospheric potential, ionization, conductivity, air-earth current, and radioactivity; of earth-currents on specially constructed lines or on existing telegraph-lines; of aurora through visual observations, spectroscopic observations, and parallactic photographs; of radio electricity through observations and records of the height of the ionized regions of the upper atmosphere, of atmospherics, and of the intensity of radio signals; and finally of cosmic radiation at some stations.

Referring to Figures 1 and 2, existing stations taking part are indicated by black circles and special stations by black triangles. It was not possible for each of these stations to arrange for the full program in the several fields, but in general the magnetic program is complete at each. The following stations are actively taking part in the atmospheric-electric program: Watheroo, Huancayo, College-Fairbanks, Tucson, Antipolo, Amberley, Apia, Fort Rae, and Chesterfield Inlet. The wide distribution of these stations will supply data in terrestrial electricity such as never before have been obtained, and the discussion of these must aid greatly the present limited understanding especially of earth-currents.

As was to be expected, stations cooperating in this effort are most numerous in the northern hemisphere as is shown by Figure 1 which indicates only the magnetic and electric stations specially provided for this program and of the permanent stations taking part. The project has the support of 20 nations which have established some 35 special temporary magnetic and electric stations, as well as a very large number of stations where attention is being given solely to meteorological work. Besides the temporary magnetic and electric stations, there are over 60 existing permanent magnetic and electric observatories taking part, thus bringing the total number of widely distributed stations in all parts of the world cooperating in the magnetic and electric program to nearly 100. Then, too, there are many hundreds of specially established and permanently established meteorological stations taking part in the extensive meteorological program. A notable contribution to the Polar-Year program is that being made by the establishment of 92 special stations by the U.S.S.R.--six of these were specially established and equipped for the magnetic and electric program and 26 are reported fully equipped for auroral observations.

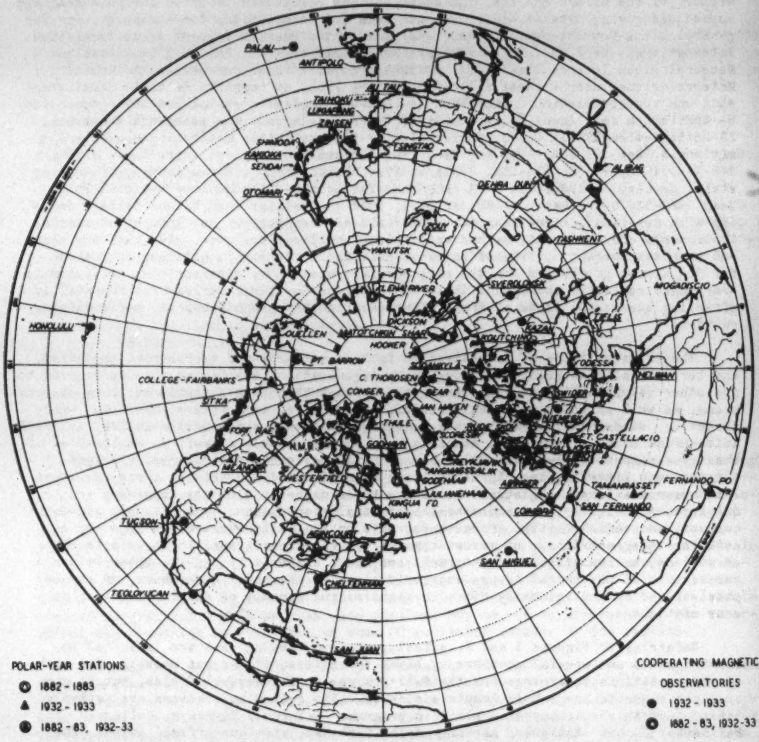


Fig. 1--Established magnetic and electric observatories and special International Polar-Year stations, 1882-83 and 1932-33, northern hemisphere

Figure 2 shows the distribution of temporary and permanent magnetic and electric stations in the southern hemisphere. Considering the fact that the Pacific Ocean is so large a part of the southern hemisphere with relatively few available sites, it will be noted that the number of stations in that hemisphere is about one-third of the total.

Table 1 lists the magnetic and electric observatories with their approximate positions, including under A the specially established stations for the Polar Year and under B the permanent stations which are taking part. The table also indicates those stations for which the specially designed rapid-speed magnetograph-recorders and specially designed low-sensitivity recorders have been provided by the International Polar Year Commission.

The United States is participating in the program through the operation of two special stations, the one designated as the College-Fairbanks station in Alaska, provided for by an act of Congress appropriating $30,000, and the second the station established at Point Barrow, Alaska, as a reoccupation of the station at that place occupied by the United States during the first International Polar Year of 1882-83.

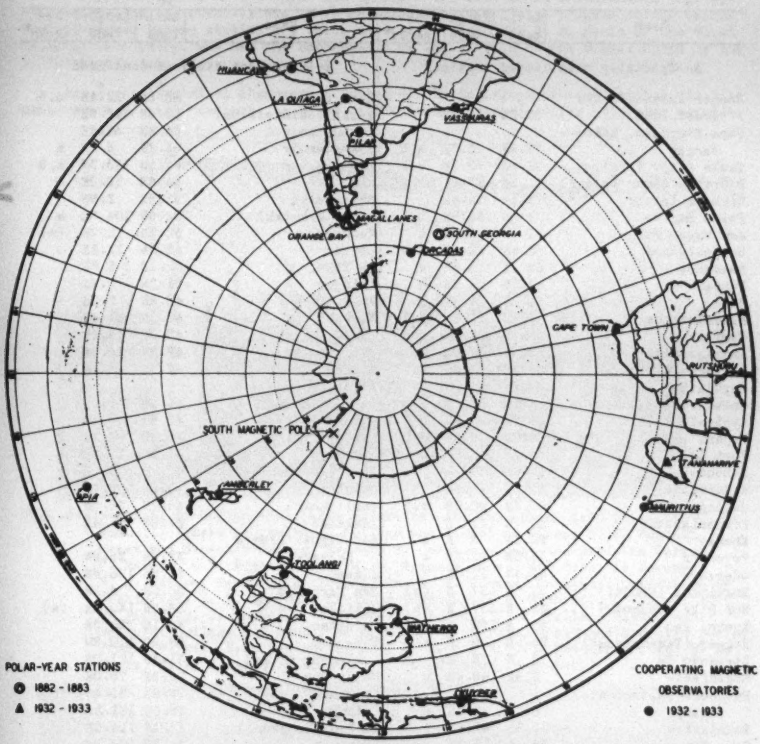


Fig. 2--Established magnetic and electric observatories and special International Polar-Year stations, 1882-83 and 1932-33, southern hemisphere

The College-Fairbanks station is under the direction of the United States Coast and Geodetic Survey, and was made possible by the united efforts of the State Department, the Department of Commerce through its Coast and Geodetic Survey and Bureau of Standards, the War Department through its radio station at Fairbanks, the Navy Department through its Naval Research Laboratory, the Department of Agriculture through its Weather Bureau, the Carnegie Institution of Washington through its Department of Terrestrial Magnetism, the Alaska Agricultural College and School of Mines, the International Polar Year Commission, and contributions from individuals totaling over $2,600. The appropriation was not made available until July 1, 1932, but despite this the buildings were constructed and the instrumental equipment was installed so that the complete program of continuous registration was begun October 1, 1932.

The program at the College-Fairbanks station is a most comprehensive one including magnetic variation and absolute measurements, earth-current records, detailed visual and photographic auroral observations, measurements of variations in magnetic vertical-intensity by the Mitchell-loop method, atmospheric potential-gradient, air-conductivity, ionic content, Aitken nuclei-counts, and radio measurements on the height

Table 1--Stations International Polar Year of 1932-1933
and approximate geographic positions

Name	Latitude	Longitude	Remarks*
A--Specially established stations			
Hooker Island, Franz Josef Land	80.3N	52.8E	
Cape Thordsen, Spitzbergen	77.9N	16.7E	a,b
Thule (Cape York)	76.1N	69.1W	a,b
Björnöya (Bear Island)	74.5N	19.2E	a
Dickson Island	72.5N	82.4E	
Point Barrow	71.4N	156.3W	b
Jan Mayen Island	71 N	8 W	a
Scoresbysund	70.5N	22.0W	a,b
Bossekop	69.8N	23.3E	a
Petsamo	69.5N	31.2E	a
Bodö	67.3N	14.4E	a
Kandalakscha	67.1N	32.4E	a
Ouellen	66.2N	169.0W	
Angmagssalik	65.6N	37.6W	a,b
College-Fairbanks	64.9N	147.8W	a,b
Reykjavik	64.8N	21.8W	a
Chesterfield Inlet	63.8N	91.8W	a,b
Lycksele	64.7N	18.8E	a
Kajani	64.2N	27.5E	a
Fort Rae	62.7N	116.8W	a
Yakoutsk	62.0N	129.7E	
Kajortalik	61.2N	48.5W	
Julianehaab	60.7N	46.0W	a,b
Frederikstad	59 N	11 E	
Manhay	50.3N	3 E	a
Toyohara	47.0N	142..7E	a
Odessa	46.4N	30.8E	
Mukaiyama (Sendai)	37 N	137 E	(a)
Bun Rika (Shimoda)	35 N	137 E	(a)
Kyoto, Aso	35 N	135 E	(a)
Hoggar (Tamanrasset)	25 N	5 E	a
Fernando Po	3 N	6 E	
Mogadiscio	2.0N	45.4E	a
Rutshuru (Elisabethville)	5 S	20 E	a
Tananarive	18.9S	47.5E	a
Cape Town	34 S	18.2E	a
Magallanes (Punta Arenas)	53.2S	70.9W	a
B--Permanent stations			
Matotschkin Shar	73.3N	56.4E	
Tromsoe	69.6N	18.9E	a
Godhavn	69.2N	53.5W	a,b
Abisko	68.4N	18.8E	a
Sodankylä	67.4N	26.6E	a
Dombaas	62.1N	9.1E	
Lerwick	60.1N	1.2W	a
Sloutzk	59.9N	30.3E	a
Lovö	59.4N	17.8E	a
Sitka	57.0N	135.3W	
Sverdlovsk	56.8N	60.6E	

Name	Latitude	Longitude	Remarks*
B--Permanent stations-Continued			
Rude Skov	55.8N	12.4E	a,b
Kazan (Saimistsche)	55.8N	48.8E	
Koutchino	55.8N	37.6E	
Eskdalemuir	55.7N	3.2W	a
Meanook	54.6N	113.3W	a,b
Hel	54.6N	18.8E	
Stonyhurst	53.8N	2.5W	
Zouy (Irkutsk)	52.3N	104.3E	a
Neimegk	52.1N	12.7E	(a)
Swider	52.1N	21.2E	
De Bilt	52.1N	5.2E	
Abinger	51.2N	0.4W	
Val Joyeux	48.8N	2.0E	a
Maisach	48.2N	11.6E	
Auhof (Vienna)	48.2N	16.2E	
Stará Dala	47.9N	18.2E	
Nantes	47.2N	1.6W	
Forte Castellacio (Genoa)	44.4N	8.4E	
Agincourt	43.8N	79.3W	
Karsani (Tiflis)	41.8N	44.7E	
Tashkent	41.3N	69.3E	
Ebro (Tortosa)	40.7N	0.5E	a
Coimbra	40.2N	8.4W	
Cheltenham	38.7N	76.8W	
Ashkabad	37.9N	58.4E	
San Miguel (Ponta Delgada)	37.8N	25.6W	a
Zinsen	37.5N	126.6E	
San Fernando	36.5N	6.2W	
Kakioka	36.2N	140.2E	(a)
Tsingtao	36.1N	120.3E	
Tucson	32.2N	110.8W	
Lukiapang (Zosé)	31.3N	121.0E	
Dehra Dun	30.3N	78.0E	
Helwan	29.9N	31.4E	
Taihoku	25.0N	121.5E	
Au Tau (Hongkong)	22.4N	114.0E	
Honolulu	21.3N	158.1W	
Teoloyucan	19.8N	99.2W	
Alibag	18.6N	75.9E	
San Juan	18.4N	66.1W	
Antipolo	14.6N	121.2E	
Palau	7.3N	134.5E	
Kuyper (Batavia)	6.2S	106.8E	
Huancayo	12.0S	75.3W	a
Apia	13.8S	171.8W	
Mauritius	20.1S	57.6E	
La Quiaca	22.1S	65.6W	
Vassouras	22.4S	43.6W	
Watheroo	30.3S	115.9E	a
Pilar	31.7S	63.9W	
Toolangi	37.5S	146.5E	
Christchurch (Amberley)	43.5S	172.6E	a
Orcadas	60.7S	44.8W	

*Entries show those stations for which specially designed Polar-Year magnetographs have been installed; a indicates la Cour open-time-scale type; (a) indicates open-time-scale type of another design; b indicates low-sensitivity set.

of the ionized regions of the upper atmosphere. The last-named measurements together with meteorological observations on an enlarged and intensified program at the United States Weather Bureau station are being made at Fairbanks by H. B. Maris of the Naval Research Laboratory, who has the cooperation of the station of the Signal Corps of the United States Army there.

Among the electrical phenomena observed at the College-Fairbanks station the measurement of earth-currents is being particularly stressed, using apparatus provided

Fig. 3--Personnel of College-Fairbanks Polar-Year Station (Back, left to right--C. E. Bunnell, Alaska Agricultural College and School of Mines; H. F. Bennett, Coast and Geodetic Survey; Everett R. Johnson, Coast and Geodetic Survey; C. Marcus, U.S. Signal Corps; W. W. Spencer, Coast and Geodetic Survey; W. W. Walton, Rockefeller Foundation; W. J. Rooney, Carnegie Institution of Washington; K. L. Sherman, Carnegie Institution of Washington. Front, left to right--H. J. Thompson, U.S. Weather Bureau; V. R. Fuller, Alaska Agricultural College and School of Mines; F. P. Ulrich, Coast and Geodetic Survey; Frank Pollock, U.S. Weather Bureau; R. L. Frost, U.S. Weather Bureau; H. B. Maris, Naval Research Laboratory; C. E. Johnson, U.S. Navy)

Fig. 4--Alaska Agricultural College and School of Mines with Polar-Year buildings at right

Fig. 5

Fig. 5--W. W. Spencer and P. P. Ulrich adjusting Helmholtz coil over variometer H3

Fig. 6--K. L. Sherman and air-conductivity apparatus

Fig. 7--Ion-counter and potential-gradient apparatus

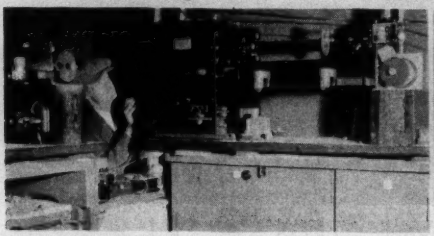


Fig. 6

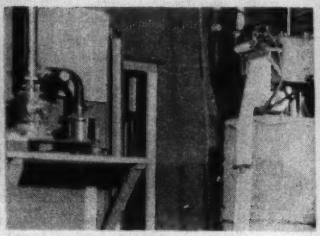


Fig. 7

Fig. 8

Fig. 8--H. B. Maris and C. E. Johnson at radio-direction instrument

Fig. 9--Aurora spectroscope-building and 10-inch telescope

Fig. 10--C. Marcus at radio transmitter and cathode-ray oscillograph

Fig. 9

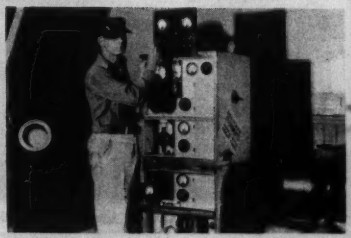


Fig. 10

and installed by the Carnegie Institution of Washington; the records already received indicate that interesting data, both on diurnal variation and short-period disturbances, may be expected.

The effective coordination and cooperation which made possible the establishment of the College-Fairbanks station may be appreciated from the group view of Figure 3 showing the men who were responsible for the actual construction of buildings and installation of equipment both at College and at Fairbanks. Figure 4 is a general view of the buildings of the Alaska Agricultural College and School of Mines at College with some of the magnetic and electric buildings in the foreground. Figure 5 shows part of the magnetograph equipment at College. Figures 6 and 7 give interior views of the atmospheric-electric observatory at College, the first showing apparatus for measuring air-conductivity and the second apparatus for measuring ionic content. Figures 8, 9, and 10 show the radio hut built at Fairbanks and interior views of the radio equipment. (The views of Figures 3 to 10 are from photographs made by F. P. Ulrich of the Coast and Geodetic Survey.)

The station at Point Barrow, Alaska, was established through the cooperation of the United States Weather Bureau, the Carnegie Institution of Washington through its Department of Terrestrial Magnetism, and the International Polar Year Commission. Four earth-current stations were also established in the United States by the American Telephone and Telegraph Company centering at Houlton, Maine; New York, New York; Wyanet, Illinois, and Tucson, Arizona. The Blue Hill Observatory and the Appalachian Mountain Club have also arranged for participation by auroral, radio, and meteorological work at Blue Hill, Massachusetts, and on Mount Washington, New Hampshire, during the present winter in cooperation with the Polar-Year program.

The United States Weather Bureau, in addition to an intensified program of observations at 86 of its first-order stations, is obtaining at 13 of these points a special auroral series of observations including spectroscopic observations and at three of the stations (Fairbanks, Nome, and Point Barrow) parallactic photographs. It is interesting to note that the meteorological contribution from the United States involves, in addition, 200 first-order meteorological stations and more than 4,000 cooperative climatological stations.

Four special stations were established in Canada. Three of these were established by the Canadian Meteorological Service, namely, the main station at Chesterfield Inlet (in full operation from October 1), and meteorological and auroral stations at Copper Mine on Coronation Gulf in the Arctic Ocean and at Cape Hope's Advance on Hudson Strait. That Service is also securing data from its regularly established stations. The fourth special station in Canada was established at Fort Rae by the British Meteorological Office and has been in operation from August 1.

The University of Michigan has established a meteorological and auroral station in Greenland. In South America, Chile has established a station at Magallanes not far from the station of 1882-83 at Orange Bay.

In addition to these special stations the various functioning observatories of Canada, United States, Mexico, Peru, Brazil, and Argentina are carrying on special programs in addition to their regular work.

The Carnegie Institution of Washington has also cooperated with the International Polar Year Commission through the installation of special high-speed recording magnetographs in addition to the regular equipment at its observatories in Peru (Huancayo) and in Western Australia (Watheroo). The Institution has also equipped these two observatories with special power-plants and apparatus for the investigation of fluctuations in height of the ionized regions of the upper atmosphere. This has been done not only for the potential-gradient program but particularly in view of the relationship which undoubtedly exists between the ionized regions and terrestrial-magnetic phenomena. With the cooperation of the United States Bureau of Standards, the Department of Terrestrial Magnetism designed and constructed such equipment utilizing the pulse-retardation method devised by Breit and Tuve in the Department's laboratory, with improvements suggested by the later developments in the Bureau of Standards.

Besides the support of the various governments of the several international bodies interested and of private individuals and organizations, the International Polar Year

Commission has received a grant of $40,000 from the Rockefeller Foundation for the purchase of special apparatus for magnetic and electric registrations and for the meteorological work. In addition, there have been received special grants from the International Meteorological Organization and the International Union of Geodesy and Geophysics for the purchase of instrumental equipment. It is due in a large measure to these generous contributions that many more stations than would otherwise have been the case were equipped with special apparatus including particularly quick-run, open-time-scale recorders. Table 1 indicates those stations for which special equipment was provided through this grant. The grant of the Rockefeller Foundation was made with the understanding that upon completion of the Polar-Year activities this special equipment would be available for use at other observatories and to equip new observatories. It is hoped that many of the special stations established for the Polar Year may be continued on a permanent basis and thereby effect the greatly needed wider distribution of observatories so essential to improved knowledge of magnetism and electricity of the Earth.

It is apparent that the discussion of the data obtained at so many stations will present even greater problems than those of planning and realizing the establishment of the stations and of the program. The Commission will hold a meeting in May 1933 to consider the best means for the general assembly, coordination, and distribution for discussion of the resulting data, which are to be compiled and published by the governments and organizations maintaining the various stations. It is hoped that means will be forthcoming to permit undertaking promptly thorough discussion in each field under the direction of outstanding specialists.

During the May 1933 meeting there will be discussed at Copenhagen not only these matters but also the possibility of obtaining favorable action by various governments looking towards making permanent some of the stations specially established for the period of the Polar Year, as well as the real need for the continued maintenance of the existing observatories and especially for some of those the continuance of which may be threatened by the present economic conditions. It is to be hoped that the American Geophysical Union may place itself on record by suitable resolutions voicing its judgment as regards this matter and particularly as regards the extension of every facility of the United States and its organizations to the International Polar Year Commission in such steps as it may decide upon for undertaking and forwarding the investigation and distribution of the great store of geophysicel data which will have been accumulated upon the completion of the Polar Year.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

PROGRESS OF WORLD-SURVEY OF COSMIC RAYS

Arthur H. Compton

In the summer of 1930, R. D. Bennett, then of the University of Chicago, J. C. Stearns of the University of Denver, and the writer initiated a coordinated study of the geographical distribution of the cosmic rays. (A more complete record of this survey as of January 1, 1933, has been published in Phys. Rev., v. 43, 387, 1933.) Previous studies of the relative intensity of the cosmic rays in different parts of the world have been made by J. Clay (J. Clay, Amsterdam, Proc. Akad. Wet., v. 30, 1115, 1927, and v. 31, 1091, 1928), who made several trips between Java and Holland, and who found consistently a lower intensity near the equator; Millikan and Cameron (R. A. Millikan and G. H. Cameron, Phys. Rev., v. 31, 163, 1928), who found but small and doubtful differences between Bolivia and California in their measurements in mountain lakes, and no difference (R. A. Millikan, Phys. Rev., v. 36, 1595, 1930) between Pasadena and Churchill, close to the north magnetic pole; Bothe and Kolhörster (W. Bothe and W. Kolhörster, Berlin, Sitzber. Akad. Wiss., Physik. math. Kl., 450, 1930), who carried a counting tube from Hamburg (53° north) to Spitzbergen (81° north) and back, and who detected no variations in the cosmic rays larger than their rather large experimental error; Kennedy, who under Grant's direction (Kerr Grant, Nature, v. 127, 924, 1931) carried similar apparatus from Adelaide, Australia, to Antarctica, and likewise found no measurable change; and Corlin (A. Corlin, Lund Medd., No. 121,

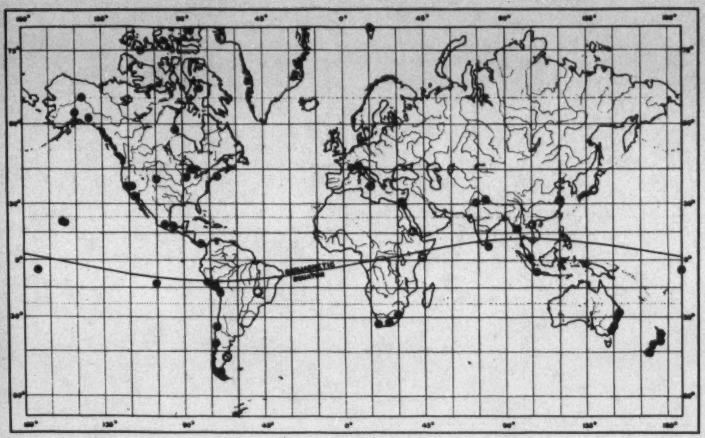


Fig. 1--Map showing location of our major stations for observing cosmic rays (Solid circles show stations completed and open circles those projected)

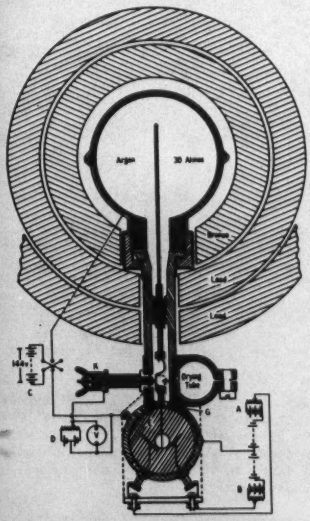


Fig. 2--Diagram of cosmic-ray ionization-chamber and electrical connections

1930), who on going from 50° north to 70° north in Scandinavia found some evidence of a maximum at about 55° north. The prevailing opinion regarding the significance of these measurements has thus been expressed by Hoffmann (G. Hoffmann, Physik. Zs., v. 32, 633, 1932. Hoffmann mentions also--without reference--that in their airship-flight over the north pole Malmgren and Behounek observed the normal cosmic-ray intensity throughout the flight.) in a recent summary, "The results so far have on the whole been negative. Most of the observers conclude that within the errors of experiment the intensity is constant and equal, and those authors who do find differences give their results with certain reservations."

In view of the strong indication from the Bothe-Kolhörster double-counter experiment (W. Bothe and W. Kolhörster, Zs. Physik, v. 56, 751, 1929) that the cosmic rays are high-speed electrical particles, this failure to find a variation of cosmic-ray intensity with latitude was of unusual interest. If the negative results of the experiments could be established with higher precision, it would mean that the cosmic rays could not be electrical particles coming from outside the Earth's atmosphere, unless these particles had an unsuspectedly high energy. If, on the other hand, further experiments should confirm the tentative findings of Clay and Corlin, it might be found that a consistent theory of cosmic rays could be built on the assumption of high-speed electrical particles entering the Earth's atmosphere.

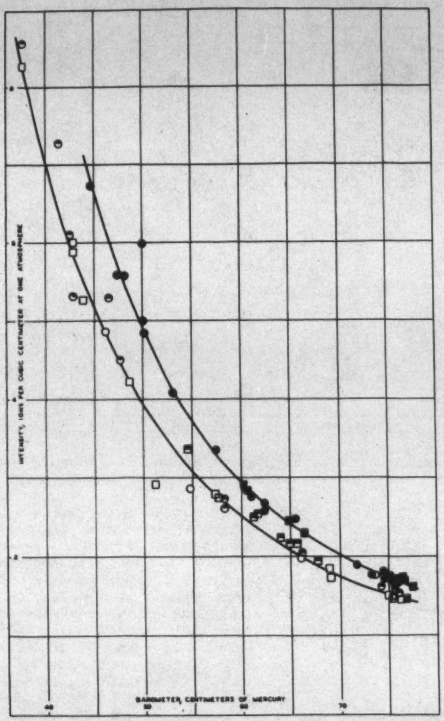
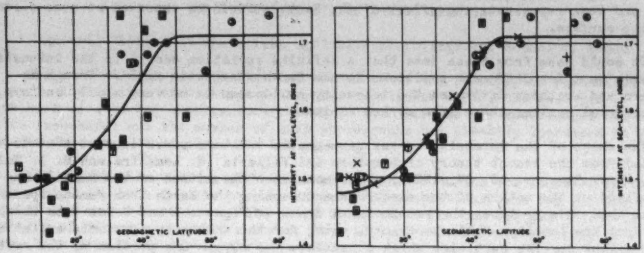


Fig. 3--Intensity of cosmic rays at various altitudes as observed in different parts of the world (stations in southern hemisphere represented by squares and in northern hemisphere by circles--white symbols for tropics and black symbols for temperate and polar zones)

There were also the well-recognized possibilities that the cosmic rays originate in the Earth's upper atmosphere. In this case systematic geographical differences might be expected, showing intensities differing perhaps over continental as compared with oceanic areas, or with the geographic latitude.

In order to get as extensive data as possible in the minimum time, several expeditions were organized to go into different parts of the world. Seven similar sets of apparatus were constructed, and measurements by the different observers were made with essentially the same procedure. The work has been done not only at sea-level, but also at as great a variety of altitudes as possible, in order to learn whether the intensity-altitude relation was independent of the location.

Eight of these associated expeditions have so far reported data. They have been under the direction of and in localities as follows: (1) J. C. Stearns and A. H. Compton, working in Colorado and Switzerland; (2) A. H. Compton, in Hawaii, New Zealand, Australia, Panama, Peru, Mexico, northern Canada, Michigan, and Illinois; (3) R. D. Bennett, Massachusetts Institute of Technology, in Alaska, California, Colorado,



Figs. 4 and 5--Intensity of cosmic rays at sea-level and latitudes 44° south to 78° north, measured by various observers, showing minimum near the equator (left), and same data plotted against geomagnetic latitude with curve as calculated from Lemaître-Vallarta (right)

and Cambridge; (4) E. O. Wollan, University of Chicago, in Chicago, Spitzbergen, and Switzerland; (5) Allen Carpe, of New York City, in Alaska; (6) S. M. Naude, University of Cape Town, in South Africa; (7) J. M. Benade, Forman Christian College, Lahore, in India, Ceylon, Malaya, Java, and Ladakh; and (8) P. G. Ledig, Department of Terrestrial Magnetism, Carnegie Institution of Washington, in South America.

The locations of the major stations where measurements have been made and reported are shown in Figure 1.

A diagram of the apparatus used in this survey is shown in Figure 2. It consists of a spherical, steel ionization-chamber, filled with argon gas at 30-atmospheres pressure, and connected with a Lindemann electrometer, which measures the ionization-current. Heavy spherical shells of lead and copper protect the ionization-chamber from gamma-rays from local sources. For standardizing the measurements, a capsule containing a small quantity of radium is placed one meter from the center of the ionization-chamber. The gamma-rays entering the chamber serve as a standard relative to which the cosmic rays can be measured at any location. There is always a certain amount of ionization due to radioactivity in the ionization-chamber itself. This has recently been measured by carrying each set into a tunnel where it was shielded by not less than 100 meters of rock.

In Figure 3 is shown a group of curves representing the variation of the intensity of the cosmic rays with altitude as we have found them in different locations. In this figure has been included all the data so far reported by our various expeditions. (The data reported in this and later figures differ from those in our previous report--Phys. Rev., v. 43, 387, 1933--due to corrections for the contamination of the walls of the ionization-chambers. As measured in deep tunnels for Nos. 1, 2, 3, 4, 5, 6, 7, and 8, these corrections are 0.01, 0.14, 0.11, 0.85, 0.01, 0.14, 0.02, and 0.14 ion, respectively.) It will be seen that all the curves have a similar shape, representing rapid increase in intensity with altitude. It will be noticed also, however, that the lowest curves are all taken in tropical regions and the highest curves in temperate or polar regions. Knowing the shape of the altitude-intensity curves, the value at sea-level corresponding to the observed intensity at any level corresponding to the observed intensity at any other altitude can be estimated. Thus we can plot these data against the latitude if we reduce each observation to its equivalent value at some standard altitude, such as sea-level.

Figure 4 shows the data for barometric pressures greater than 67.5 cm thus reduced to sea-level values, plotted against the geographic latitude. In general, it is clear that the low latitudes show less intensity than do the higher latitudes. There is, however, considerable variation from the smooth curve drawn through the experimental points. When, on the other hand, we plot the sea-level intensity against the geomagnetic latitude, as shown in Figure 5, it will be seen that the data fall more nearly upon a smooth curve. This geomagnetic latitude is taken as the distance

from the magnetic equator drawn between the poles of the Earth's uniform magnetization, and thus represents the effect of the Earth's field as observed at some distance from its surface.

It would seem from these data that a definite variation occurs in the intensity of cosmic rays for different positions in the Earth's magnetic field. Though in northern and southern latitudes the intensity would seem to be very nearly uniform, in equatorial regions there is a marked minimum.

The shape of the intensity versus geomagnetic latitude-curve is just that to be expected from the recent theory of Lemaître and Vallarta (G. Lemaître and M. S. Vallarta, Phys. Rev., v. 43, 87, 1933), which considers the effect of the Earth's magnetic field on the motion of the electrons approaching the Earth from remote space. To show that this is true, the smooth curve drawn in Figures 4 and 5 has been calculated from the Lemaître-Vallarta theory, using for the arbitrary constants suitable energy-values for the particles which constitute the rays. One portion of the radiation (82 per cent) is assumed to be unaffected by the Earth's magnetic field, while another (18 per cent) consists of electrons with a broad band of energies in the neighborhood of 7×10^9 electron-volts. The excellent agreement between this curve and the experimental data means that the variation of cosmic-ray intensity with latitude is that to be expected if a considerable portion of the ionization at high latitudes is due to electrons coming from remote space.

Our data for this world-survey are as yet by no means complete. We have at the present writing four additional expeditions in the field securing new data similar to that described above. These are: J. M. Benade, who is continuing his measurements from India to the United States via Malaya, China, Japan, and Hawaii; P. G. Ledig, who is continuing his trip around South America; D. la Cour, whose Polar-Year expedition in northern Greenland is taking cosmic-ray data near the geomagnetic pole; and Bruno Rossi, who is making measurements in Italy and northern Africa. Thomas C. Poulter is also ready to make measurements of cosmic rays with our apparatus in Antarctica, with Byrd's new Antarctic Expedition. When this work is complete, we shall be prepared to make more intensive and long-period observations at a selected group of typical stations.

Although many individuals and organizations have cooperated in this study, it was a grant from the Carnegie Corporation, for expenditure through the Carnegie Institution of Washington, which made possible extending the survey to a world-wide scale.

University of Chicago,
Chicago, Illinois

PROGRESS-REPORT ON MT. WASHINGTON OBSERVATORY

Charles F. Brooks

This report is included with the corresponding report by the author presented before the Section of Meteorology.

REPORTS ON MAGNETIC AND ELECTRIC WORK OF ORGANIZATIONS IN THE UNITED STATES DURING 1932-33

Auroral Station at the Alaska Agricultural College and School of Mines

The work at this Auroral Station, sponsored by the Rockefeller Foundation and the Carnegie Institution of Washington, has been continued during the past year. The regular work of securing simultaneous photographs of aurorae for measurement has been quite successful and the number of such photographs has steadily increased in spite of the low frequency of displays for the year.

The visual observations at half-hourly intervals during the hours of darkness have been continued, both for the purpose of securing statistical data and for the preparation of the auroral section of the daily URSIgrams. The two systems of charts for the plotting of visually observed aurorae, that of Professor Störmer and that of Dr. la Cour, have been tried during the past winter.

The location of the Polar-Year Station, College-Fairbanks, has given an opportunity, not previously had, of making a close comparison of auroral displays with magnetic and earth-current records. This comparison is being made on a basis of half-hourly intervals and promises to yield gratifying results. It is hoped that a similar comparison between visual auroral observations and Kennelly-Heaviside layer-height measurements, made by the Polar-Year unit in Fairbanks, may also be made this year.

The systematic recording of data on the reception of signals from NAA at Arlington has been continued, and because of the erratic nature of the reception at times a record is kept of reception from other points of the compass when irregularities in reception are indicated. These data have not, as yet, been put to use, but they seem to be of sufficient interest to warrant continuance of these records.

Veryl R. Fuller,
Professor, Department of Physics

College, Alaska, April 1933

Magnetic work of the United States Coast and Geodetic Survey

Magnetic surveys--During the past year, observations for the determination of the change of the Earth's magnetism with time has continued the principal feature of the field-work in terrestrial magnetism. In 1932 observations were made in the southern states from South Carolina to Louisiana and in the states bordering on Lake Michigan, for the most part the reoccupation of old stations. In only a few cases were suitable triangulation-stations available at which to establish magnetic stations for future use as repeat-stations. The program of work begun in January, 1933, extending from Virginia to Texas, follows modern arcs of triangulation for much of the way, so that triangulation-stations can be used to a much greater extent.

Declination-observations with compass-declinometer have been made at many stations in connection with the hydrographic and topographic surveys in Alaska and Philippine Islands. A more detailed investigation was made of the area of marked local attraction near Duke Island, Revillagigedo Channel, Southeastern Alaska. Observations at many places on shore and aboard ship indicate that the disturbance extends for a considerable distance out into the channel from East Island, the place of greatest disturbance.

Observatories--The five magnetic observatories have continued in satisfactory operation, with further improvements in buildings and equipment.

At Cheltenham the lower part of the framing of the building for office and absolute observations was found to be honeycombed by termites, and it has been replaced by a new and somewhat larger building, to provide more adequate and convenient space for the purposes indicated. As Cheltenham has been designated as the standardizing observatory of the United States for international comparisons of instruments and is the base-station for the standardization of the field-instruments of the Coast and Geodetic Survey, the temporary test-building has been replaced by a small comparison-and-test building designed to meet the needs of these functions.

The wooden buildings at San Juan suffered considerable damage in the hurricane of September 25, 1932, fortunately without injury to instruments or interruption of operation. To guard against future damage, the absolute and variation buildings are being encased in concrete.

At Tucson, Arizona, the observations of atmospheric electricity and earth-currents have continued, thanks to the cooperation of the Carnegie Institution of Washington, the American Telephone and Telegraph Company, and the Mountain States Telephone and Telegraph Company. This Observatory has continued to furnish reports of magnetic character of days for the daily radio broadcast of cosmic data sent out under the auspices of Science Service. At Honolulu, the temperature-compensation of the H-variometer was completed. The new magnetograph at Sitka is functioning well. Auroral observations have been continued to the limited extent possible under the unfavorable meteorological conditions prevailing at Sitka.

College-Fairbanks Polar-Year Station--The appropriation of $30,000 for participation by the United States in the Second Polar-Year program did not become available until July, 1932, but detailed plans for the work had been made in advance so that it was possible to begin construction of the buildings on August 1, 1932, and to install and adjust the instruments during September so that nearly all parts of the work were in satisfactory operation early in October. The work is being carried on under the direction of the Coast and Geodetic Survey, as provided in the enabling act, but a number of other organizations have contributed in various ways to make possible a well-balanced program of observations in terrestrial magnetism, atmospheric electricity, earth-currents, auroras, radio transmission, Kennelly-Heaviside layer, and meteorology.

The temporary magnetic observatory on the grounds of the Alaska Agricultural College and School of Mines at College is being operated by the Coast and Geodetic Survey. It is equipped with three la Cour magnetographs, each consisting of D-, H-, and Z-variometers and a recorder. One is operated at ordinary sensitivity with drum revolving once a day; one at low sensitivity with drum revolving once a day; the third at ordinary sensitivity with drum revolving once in two hours. Scale-values are determined by means of Helmholtz-Gaugain coils. Absolute observations are made with a Coast and Geodetic Survey type magnetometer and an earth inductor of the Carnegie Institution of Washington type. A dip circle is available as a reserve instrument for observations of dip and relative total intensity. Preliminary results indicate that the variometers are stable and nearly compensated for temperature and that the control-observations are adequate.

Publications--Lack of funds has necessitated temporary suspension of publication of results obtained both in the field and at observatories. The computations are being advanced steadily and the results prepared for publication. The field-results for 1931 are ready and those for 1932 nearly completed. The computations of observatory-results for Cheltenham, Tucson, Sitka, and Honolulu are practically completed for 1927 and 1928 and well advanced for 1929 and 1930.

R. S. Patton,
Director

Washington, D. C., April 27, 1933

Magnetic investigations of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, May 1932 to April 1933

Work in the field and at observatories

Magnetic survey and cooperation--Under the direction of F. C. Brown of the American Church Mission at Hankow, assisted by C. T. Kwei of Central China College at Wuchang, good progress was made in the cooperative field-work with the Department. Results from 27 stations have been received. Observations to compare the C.I.W. instruments being used by Brown and Kwei and the instruments of the Lukiapang Observatory, as well as the new instruments acquired by this Observatory to be used at Zose, whence the Lukiapang Observatory is being transferred, were made. The newly purchased modern instruments for the magnetic work of the National Academy of Science at Peiping were tested and preliminary intercomparisons were made.

The cooperation with the Meteorological Service of East Africa through Director A. Walter of that Service has been continued in the occupation of seven stations.

Green completed his field-work in South America, returning to Washington in June 1932. Contacts with officials interested in terrestrial magnetism were made in various countries. Intercomparisons of instruments were effected in Brazil, Argentina, and Chile. In Chile assistance was given J. Valenzuela, Director of the Meteorological Service, in his successful efforts in cooperation with the International Polar Year Commission and the Department to establish a Polar-Year station at Magallanes. P. G. Ledig of the Department spent some six weeks (March and April 1933) at Magallanes assisting the Chilean observers to develop the program at the Observatory and with them secured a series of observations to determine constants and corrections on standards of the Observatory's absolute instruments. Earl Hanson of the Department completed the reoccupation of magnetic stations in Venezuela, Brazil, Peru, Ecuador, and Colombia early in 1933 and returned to Washington. The results of the three expeditions of Green, Hanson, and Ledig have furnished valuable data for secular-variation investigations in South America--a region now showing unusual accelerations in secular changes.

Eclipse expedition of August 31, 1932--In continuance of the Department's studies to determine possible effects on the Earth's magnetic field, three stations were established in Maine and Vermont under the general direction of the late Harlan W. Fisk. A comparison of the graphs drawn from the observations at the three stations showed a close identity of features. One of these features immediately following totality suggests magnetic eclipse-effect.

International Polar-Year 1932-1933--Preparations for the International Polar Year occupied much of the time of a number of the staff in the first half of 1932. The assembling of pertinent facts and their presentation before the committees of Congress aided in securing appropriations for participation of the United States in the work. General plans for the construction and operation of the College-Fairbanks station were carried out in cooperation with the United States Coast and Geodetic Survey, the Naval Research Laboratory, and the Alaska Agricultural College and School of Mines. This work included plans for buildings and equipment, construction and testing of instruments, and instruction of observers. Earth-current equipment for this station and for the Canadian station at Chesterfield Inlet was assembled and tested, and memoranda on the layout and operation of similar measuring systems were supplied to other stations. Fairly complete atmospheric-electric equipment was supplied for the College-Fairbanks station.

For the Polar-Year program additional variometers of the la Cour type were installed at the Huancayo Magnetic Observatory. E. R. Johnson of the Coast and Geodetic Survey, in charge of the cooperative College-Fairbanks station, and C. J. McGregor, who is occupying the Point Barrow station of the United States Weather Bureau for which magnetic equipment was made available by the International Polar Year Commission and the Department of Terrestrial Magnetism, were given instruction in magnetic measurements and observatory-operation.

Active participation in the Polar Year was taken at the College-Fairbanks station, where Rooney and Sherman aided in the construction of the station and installation of equipment and the latter remained as observer in particular charge of the work in terrestrial electricity. Upon the request of the Meteorological Service of Canada, Davies of the Department was given furlough to take charge of the Canadian station at Chesterfield Inlet.

The program at the College-Fairbanks station is a most comprehensive one, including magnetic variation and absolute measurements, earth-current records, detailed visual and photographic auroral observations, measurements of variations in magnetic vertical-intensity by the Mitchell-loop method, atmospheric potential-gradient, air-conductivity, ionic content, Aitken nuclei-counts, and radio measurements on the height of the Kennelly-Heaviside layer. Some meteorological measurements are also being made in addition to those secured by an intensified program at the regular Fairbanks station of the United States Weather Bureau. Among the electrical phenomena the measurement of earth-currents is being particularly stressed at this station, and the early records indicate that interesting data both on diurnal variation and short-period disturbances may be expected.

Observatories--The cooperation with the Apia Observatory, Western Samoa, has been continued.

A la Cour rapid-run magnetograph was installed in January 1933 at the Huancayo Magnetic Observatory for operation during the Second International Polar Year which, for stations in the southern hemisphere, extends from January 1, 1933 to January 31, 1934.

Upon the recommendation of the Advisory Committee in Seismology of the Carnegie Institution of Washington and of the United States Coast and Geodetic Survey, a seismological station was established at the Huancayo Magnetic Observatory. The equipment, consisting of a Benioff vertical-component seismometer with a gravity-driven recorder and two Wenner horizontal-component seismometers with a double-section drum-recorder, was installed in August 1932. The Huancayo seismograms are already proving useful, not only for seismological investigation in regard to Central America but also for the location of epicenters in the Pacific Ocean off the west coast of South America.

In view of the relationship which undoubtedly exists between the ionized regions of the upper atmosphere (Kennelly-Heaviside layer) and terrestrial-magnetic phenomena, it was decided to install suitable apparatus for the study of those regions at both the Huancayo and Watheroo magnetic observatories. With the cooperation of the United States Bureau of Standards, the Department of Terrestrial Magnetism designed and constructed such equipment, utilizing the pulse-retardation method devised by Breit and Tuve in the Department's laboratory with improvements suggested by later developments in the Bureau of Standards. Installation of this equipment at Huancayo was begun in February 1933, the radio laboratory and power-equipment having been built and installed during 1932. A similar installation is under way at the Watheroo Magnetic Observatory.

At Watheroo measurements of the potential gradient have been continued at a field-station approximately 40 miles distant. A recorder after the design of A. Crichton Mitchell for registering rapid changes in the vertical intensity of the Earth's magnetic field has been put into operation. This consists of a galvanometer, recorder, and loop enclosing an area of 180 acres. The current induced in the loop by changes in vertical intensity is recorded by a sensitive galvanometer on a rapidly moving photographic tape.

Terrestrial electricity

Earth-currents--Preliminary studies of the earth-current records from the Watheroo, Huancayo, and Tucson observatories have been continued by Gish and Rooney. Some revision of the Watheroo records for 1929, 1930, and 1931, necessitated by the gradual breakdown of the insulation of the underground sections of the connecting lines and now replaced by overhead wires, has been completed. Improved operation of the measuring system at Huancayo has resulted in more complete duplicate records from that Observatory.

Comparison of the data from Watheroo and Ebro for a five-year period on the basis of selected calm and disturbed days was made by Rooney The difference in diurnal variation on disturbed and quiet days is much like that observed in similar comparisons of magnetic data--a further indication of the close relationship between the two phenomena.

Forbush completed his study of apparent vertical earth-currents at Huancayo, and Gish investigated the same subject from a theoretical standpoint in an effort to establish a possible explanation for the somewhat anomalous effects reported particularly in mountainous regions. Detailed tabulations together with analysis and discussion of the earth-current records from the Watheroo and Huancayo observatories to be published in a volume of researches are in preparation. Reduction and study of the data from Tucson are under way. With a little over one year's record now available, the types of diurnal and seasonal variation there seem fairly well established and are found to be in good agreement with records from stations in similar latitude. The extension of the Tucson measurements through the International Polar Year will afford a check on the data secured to date. Gish has maintained contact with the several series of earth-current measurements being conducted by the American Telephone and Telegraph Company in addition to its participation in the cooperative work at Tucson.

It is expected that this interchange of suggestions and data will prove most fruitful of results.

Atmospheric electricity--In addition to continuing their work on the reduction of the atmospheric-electric observations of the Huancayo and Watheroo observatories, Wait and Torreson have continued their experimental work on atmospheric pollution. Continuous registration at Washington of the large-ion and small-ion content of the atmosphere has been in progress since September 1932. Publication of the data pertaining to the relationship of these two kinds of ions is contemplated for the near future.

Wait and McNish have also constructed an apparatus by means of which the rate of production of small ions in the atmosphere is continuously recorded.

In addition to the various preparations for the program of atmospheric-electric measurements at College, Alaska, during the Polar Year, Gish and Sherman, with the aid of an assistant computer, continued preparing for publication the atmospheric-electric data obtained from the Deck Observatory at Washington, D. C., and from the Tucson Magnetic Observatory. Gish, by giving attention to some neglected factors, extended the scope of the equations which are designed to describe the ion-population of the lower atmosphere.

Laboratory investigations

Atomic nucleus and high voltage--Results have been obtained covering a wide range of experiments on atomic disintegration, including a complete and independent verification of the existence of the recently discovered neutron, using a strong radium source to bombard and disintegrate beryllium--thereby producing high-speed neutrons. The disintegration of lithium and boron into helium using high-speed protons from a high-voltage tube has been studied. Using the linear amplifier to record the disintegrations, alpha-particles of two ranges, the shorter being about two centimeters, are found to be produced when the lithium nucleus is disintegrated. The disintegration-yield from boron is much greater than from lithium, and boron also gives rise to two ranges of alpha-particles, the shorter being about three centimeters. This element gives about one disintegration alpha-particle for 4,000,000 high-speed protons (600 kilovolts) striking the target.

Observations were made on the "resonance" disintegration of aluminum using alpha-particles from polonium, an important problem in connection with the wave-theory of the atom.

The Van de Graaff type of electrostatic generator was tested, developed, and used for the studies of atomic disintegration. A special building is now under construction at the Department of Terrestrial Magnetism to house a large (2-meter) generator of this type which was built and tested there May 1932 and which is intended in addition to the one-meter-diameter generator for experiments with relatively intense beams of "artificial" neutrons.

Experiments on the neutron were made late in the summer of 1932 using a special type of amplifier similar to the amplifier of a radio receiver and a cloud-chamber apparatus which gives a fog-track picture of the paths of fast atomic fragments. These experiments verified Chadwick's conclusions that the very penetrating rays obtained from beryllium when bombarded by alpha-particles from a strong radium source cannot be gamma-rays (light-waves), but can be satisfactorily explained on the hypothesis that they are fast-moving neutrons, or inert particles, having the same mass as the hydrogen atom but no electrical charge.

Study of the disintegration of aluminum, nickel, and silver targets by 600-kilovolt protons reveals a very much smaller amount of disintegration than has previously been reported by others. The number of disintegrations observed is no larger than would be produced by a contamination of the targets by less than one part in 100,000 of boron.

Search is under way for the one-quantum isolated magnetic poles predicted by Dirac.

Investigation of compass-deviations--A large amount of experimental data on the deviations of the compass observed in a swing under different conditions of amplitude, radius, and heading has been accumulated by Peters and is now being compiled and investigated.

Investigation of cosmic rays--Assistance was given A. H. Compton in his cosmic-ray survey work in South America during July 1932 by members of the Huancayo Magnetic Observatory. Data were determined at five stations on the Central Railway of Peru from Lima (500 feet above sea-level) to Galera Tunnel (16,960 feet above sea-level), at Huaytapallacu (15,000 feet above sea-level) in the divide northeast of the Observatory including diurnal-variation observations (July 8-14, 1932), and at the summit of El Misti (19,200 feet above sea-level) as also at the rest-house en route to the summit, and at Arequipa. P. G. Ledig of the Department is taking cosmic-ray observations in Chile and Argentina while making magnetic observations at repeat-stations since December 1932. Assistance was also given T. H. Johnson of the Bartol Research Foundation in connection with his cosmic-ray work in Mexico. Continuous registration of cosmic radiation has been under way since the latter part of 1932 at the Huancayo Magnetic Observatory with apparatus developed by Cairns.

A statistical analysis by McNish of the observations of the diurnal variation of cosmic rays indicates that evidence of this phenomenon so far published is not conclusive. He has also developed statistical tests for cosmic-ray data obtained with counters.

In connection with a special grant made by the Carnegie Corporation to the Carnegie Institution, a special committee of the Institution has cooperated with R. D. Bennett, A. H. Compton, J. L. Dunham, T. H. Johnson, R. A. Millikan, and other workers in cosmic radiation abroad and in America in developing plans for systematic continuous registrations with specially designed equipment to be installed at six to eight permanent observatories and stations.

Compilation and discussion of terrestrial-magnetic data

Compilation of data at observatories--Excellent progress has been made in tabulating for publication the magnetic data from records obtained at the Watheroo Magnetic Observatory since 1919 and at the Huancayo Magnetic Observatory since 1922. The magnetic data obtained at Little America by the Byrd Antarctic Expedition in 1928-29 have been compiled.

Diurnal variation--The determination and analysis of the magnetic lunar diurnal-variation from data for the Watheroo and Huancayo magnetic observatories are in progress by Bartels.

Spherical harmonic analysis of the anomalous magnetic diurnal-variations of the western hemisphere by McNish is in progress. A current-system of the upper atmosphere considerably different over that region from the idealized system deduced by Chapman has been indicated by the results of observatories, particularly the Huancayo Magnetic Observatory. Magnetic diurnal-variations from records of those observatories situated near the 75th meridian west of Greenwich are being used in the analysis. Harmonics of higher degree may make possible an accurate representation of this anomaly.

Secular variation--Investigations of secular-variation data and isoporic changes in the Pacific Ocean and region of the Caribbean Sea initiated by Fisk are being continued by Green and Duvall. A similar discussion for the South American Continent is under way.

An investigation of the effect of magnetic activity on the secular variation of horizontal intensity indicates that the only effect is due to the post-perturbation of the element during disturbed years.

Magnetic activity--Investigations of various proposed measures of magnetic activity are being continued. Compilations according to the Stockholm resolution in 1930 are regularly kept current although preliminary discussion indicates this is not so satisfactory a measure as that based upon interdiurnal variability. The latter has been considered further by Bartels.

General--Considerable attention is being given to questions involving more rapid and effective means of reducing photographic records at observatories. Photographic apparatus is in construction which it is hoped may permit photographic compilations to greatly reduce the great labor of measurement now necessary by present methods.

The many volumes of the personal library of Louis A. Bauer, late director of the Department, have been recently donated to the Department by his widow. Among them are many early and rare works pertaining to terrestrial magnetism.

Publications

The following is a list of the more important papers published in the past year:

Bartels, J. L'activité du magnétisme terrestre et ses relations avec les phénomènes solaires. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 3-C-1, 12 pp. (1932).

-----. How changes on the Sun's surface are recorded by the Earth's magnetism. Sci. Mon., vol. 35, 492-499 (Dec. 1932).

Fisk, H. W. The unsymmetrical distribution of magnetic secular-variation. Terr. Mag., vol. 37, 235-240 (Sept. 1932).

Fleming, J. A. Time-changes in the Earth's magnetic field. Sci. Mon., vol. 34, 499-530 (June 1932).

-----. Distribution à travers le monde des observatoires magnétiques et des stations pour l'étude de la variation séculaire. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 2-C-1, 11 pp. (1932).

-----. Distribution of magnetic observatories and secular-variation stations. Terr. Mag., vol. 37, 245-251 (Sept. 1932).

-----. Summary of the year's work, Department of Terrestrial Magnetism, Carnegie Institution of Washington. Terr. Mag., vol. 37, 455-462 (Dec. 1932).

Gish, O. H. Les courants électriques naturels de l'écorce de la Terre et leur rapport avec le magnétisme terrestre. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 1-C-2, 21 pp. (1932).

-----. Observed air-earth current and maintenance of Earth's charge. Terr. Mag., vol. 37, 361-362 (Sept. 1932).

-----. Use of geoelectric methods in search for oil. Bull. Amer. Ass. Petrol. Geol., vol. 16, 1337-1348 (Dec. 1932).

Harradon, H. D. List of recent publications (terrestrial and cosmical magnetism, terrestrial and cosmical electricity, miscellaneous). Terr. Mag., vol. 37, 195-202 (June 1932); 354, 360, 416-420 (Sept. 1932); 496-503 (Dec. 1932); vol. 38, 73-78 (Mar. 1933).

Johnston, H. F., and A. G. McNish. Variations du champ magnétique terrestre aux observatoires de Watheroo et de Huancayo et leurs relations avec les systèmes de courants à l'intérieur et au voisinage de la Terre. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 2-C-3, 12 pp. (1932).

McNish, A. G. Sources of errors in the determination of the potential gradient of the Earth's electric field. Terr. Mag., vol. 37, 439-446 (Dec. 1932).

Peters, W. J. The distribution of mass in marine compasses. Terr. Mag., vol. 37, 317-320 (Sept. 1932).

Rooney, W. J. Mesures de la resistivité de la Terre et leur application à la géophysique et aux problèmes techniques. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 4-C-1, 15 pp. (1932).

-----. The significance and accuracy of measurements of earth-current potentials. Terr. Mag., vol. 37, 363-374 (Sept. 1932).

Wait, G. R. The Aitken pocket nuclei-counter. Beitr. Geophysik, vol. 37, 429-439 (1932).

Wait, G. R., and O. W. Torreson. Quelques facteurs affectant la conductibilité électrique de l'atmosphère. Cong. Internat. d'Electricité, Paris, 11e Section, Comm. No. 5-C, 10 pp. (1932).

J. A. Fleming,
Acting Director

Washington, D. C., April 27, 1933

Work related to terrestrial magnetism and electricity of the Naval Research Laboratory

From radio transmission-observations during the years 1927 and 1928, A. H. Taylor and L. C. Young summarized the skip-distances of radio waves of wave-lengths from 10 to 50 meters for summer and winter day-and-night conditions in temperate zones. From these skip-distances, E. O. Hulburt calculated the ionization in the bank at about 200 kilometers above sea-level. The average daytime maximum ionization came out to be about 6×10^5 electrons per cubic centimeter, or an equivalent number of ions and electrons. This value when compared with the value 4×10^5 determined from the skip-distances of 1923 and 1924 showed that the ionization increased about 50 per cent from the epoch of minimum to that of maximum solar activity.

H. B. Maris at the International Polar Year Station at Fairbanks, Alaska, carried on observations of spectra of the arctic sky and of the ionized layers in the upper atmosphere.

E. D. Almy, Commander, U.S.N.,
Director

Bellevue, D. C., April 20, 1933

Research in atmospheric electricity at Stanford University

An entire year of continuous records of space-charge at two elevations has now been obtained, along with continuous records of potential gradient and wind-velocity. The records have all been measured and mean curves of the diurnal variation for each month obtained. The evidence for the effect of turbulence in determining the value of the space-charge is greatly increased. It is very apparent, however, that the amount of dust in the air, the humidity, and the nuclei-content are very important factors. For this reason a more detailed record of these factors must be obtained.

During the last three months Russell A. Nielsen has been working on the design of a modified Owens jet dust-counter utilizing a Weston photronic cell. The device is intended to be continuously recording and shows promise of giving very good relative values and may even give fair absolute values.

Philip D. Williams has just about completed his laboratory study of the relative affinity of positive and negative small ions for water-vapor and nuclei. Within the limits of humidity found in the atmosphere, no evidence is found for any selective tendency. An attempt is being made to use larger aggregates, that is, fog-particles, but condensation in the ion-counter has interfered with the measurements. This difficulty, however, may be overcome.

E. A. Evans has finished his work on the mechanism of the lightning-discharge. His tests in the Ryan High-Voltage Laboratory showed a definite effect of the nature of the surface in determining the point of "striking."

Joseph G. Brown,
Professor, Department of Physics

Stanford University, April 3, 1933

AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

SECTION OF OCEANOGRAPHY

Washington, D. C.
April 28, 1933

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SUBMERGED RIVER-VALLEYS OF THE BAHAMAS

Harry Hammond Hess

In a preliminary report of the International (Navy-Princeton) Expedition to the West Indies, presented before the Union (Trans. Amer. Geophys. Union, 13th annual meeting, 28-33, 1932) last year, the great submarine valleys of the Bahamas were briefly described. Additional data collected last summer and a further study have brought to light several interesting features which are thought to be worth mentioning at this time. A full report of the results of the Expedition is to be published shortly by the Hydrographic Office of the United States Navy.

Brief description of the valleys

(1) The valleys have a northwest-southeast trend for the greater part of their lengths, but short, steep cross-valleys at right-angles to this trend connect the longitudinal valleys with the ocean proper.

(2) They slope continuously from the shallowest parts of their upper reaches at 720 fathoms (4,320 feet) to the place where they meet the ocean-basin proper at 2,500 fathoms (15,000 feet).

(3) The longitudinal valleys have gradients of 15 to 20 feet to the mile, with gently sloping undulating bottoms from 720 fathoms (4,320 feet)to 1,000 fathoms (6,000 feet).

(4) The cross-valleys or transverse valleys have steeper gradients, about 100 feet to the mile. They have the typical V-shaped cross-profile of a youthful river-valley and an inner gorge or stream-channel near the center.

(5) Where tributaries join the main stream they do so "at grade" (at the same level), a feature characteristic only of river-valleys.

(6) Where examined the edges of the valleys rise steeply perhaps as vertical cliffs from a depth of 500 fathoms to the edge of the platform.

[Note concerning accuracy of soundings--The upper part of the Tongue of the Ocean and Exuma Sound are only sparsely sounded and in many cases it was difficult to determine the ship's position with sufficient accuracy. In the northwest and northeast Providence channels and at the mouth of the Tongue of the Ocean, however, conditions were different. In this region the ship's position could be frequently checked with reference to lights and other recognizable features on shore. On the S-48 soundings were recorded by the radio-man on duty about every six minutes where cross-profiles were being made and many more soundings were taken by Brown in areas considered critical,so that for these, at least, practically continuous profiles were obtained. Only a part of these soundings appeared on the charts showing the course of the Expedition which were issued last year by the Hydrographic Office of the United States Navy.]

From this brief outline of their general features, the threefold origin of the valleys may be recognized.

First, the trellis drainage-pattern, with gently sloping longitudinal valleys and steeper, shorter transverse-valleys, indicates a structural control. What the nature of this control may be is not known. It may be a result of differential erosion of folded or tilted beds of varying durability, such as the trellis drainage-patterns found in the Appalachians on folded rocks. It may be a primary structural control; the longitudinal rivers may have flowed along and graded the floors of structural depressions, such as downwarps, synclines, or even grabens.

Second, the floors of the valleys have been graded by the action of running water under subaerial conditions. The writer wishes particularly to emphasize this point. Though many points with regard to the nature and origin of the valleys are still largely conjectural, the above-mentioned point is substantiated by such strong evidence that it seems beyond question. When the work began the writer was admittedly

skeptical that submerged river-valleys could occur at such great depths below present sea-level. As the data accumulated, however, the river-valley hypothesis continually gained support, and each of the other possible hypotheses, one by one, met with some fatal objection. Possible hypotheses to account for valley-like depressions below the sea can be grouped as follows:

(1) Structural
  (a) Graben or fault-trough
  (b) Downwarp or synclinal trough
(2) Troughs formed below the sea by the scouring action of currents on the bottom
(3) Valleys formed by subaerial erosion and later submerged

The fact that the valleys slope continuously from their upper reaches at about 720 fathoms to the edge of the continental slope where they reach a depth of 2,500 fathoms, some of them being over 100 miles long, and the fact that tributaries enter the main stream "at grade" (at the same level), definitely exclude the graben and synclinal-trough hypotheses as probable explanations. There is no reason why the floor of a graben or a syncline should slope continuously in one direction. One such valley might be explained as a freak of chance, but several valleys all exhibiting this feature, plus the fact that the tributaries enter the main stream at grade, eliminate the structural hypotheses from the realm of probability.

The efficacy of marine currents to produce any appreciable depressions on the sea-floor may well be open to doubt. Assuming they could produce such a depression, and could produce one which sloped continuously in one direction, which is still further open to doubt, it is hardly likely that they could form a valley with an inner gorge or channel running approximately down its middle as is the case in the valleys described, whereas such a feature is not uncommon in river valleys. Thus the second hypothesis is effectively eliminated, leaving only the subaerial-erosion hypothesis intact. It is not denied that depressions of the nature of (1) and (2) may have preceded subaerial erosion, and perhaps controlled it.

Third, the valleys have been peculiarly modified by the building up of calcareous reef-material from the higher parts of the old topography after the formation and submergence of the erosional valleys. In the paper presented last year, it was said that no satisfactory conclusion as yet had been arrived at to explain the steep, cliff-like walls of the valleys rising from 500 fathoms to the margin of the platform. An explanation is now available and is given below.

The transverse profiles of the submarine valleys are those of typical river-valleys up to the places where the steep cliff-like margins are approached, and these are totally unlike in form any river valleys on land (see Fig. 1). The explanation of the steep walls of the valleys must undoubtedly lie in some process which caused their upbuilding after the erosional valleys had already been formed. (The writer is indebted to Professor W. Bucher for the original suggestion of the possibility of the building or deposition of calcareous material on the higher parts of the old topography.) They are thus depositional rather than erosional features. The bottoms of the valleys, with the original stream-channels preserved, have escaped this deposition. Evidently the deposition did not begin until a submergence of something like 11,000 feet of the present 15,000 feet had taken place, or within 4,000 feet of the present

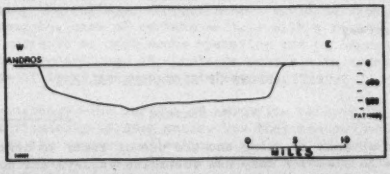

Fig. 1--A transverse profile across the Tongue of the Ocean, showing steep "reef-cliffs" rising from the rather gentle topography of the valley floor (vertical exaggeration X 4)

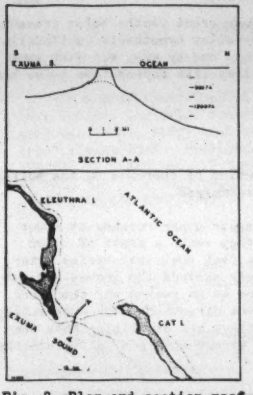

Fig. 2--Plan and section reef-isthmus between Eleuthra and Cat islands (vertical exaggeration section A-A X 2)

surface. From this level upward as submergence proceeded, the calcareous reef-material of the platform built up as fast as relative sea-level rose. It might be supposed that at first a fringing reef was formed around the edge of the still emergent higher parts of the topography. As sinking proceeded, the reef built up until the old topography was completely submerged and the top of the reef spread over it. From there on reef-building continued to keep pace with submergence, so that the platform was built up to the present surface.

This reef-platform has not been built outwards laterally from some central ridge over a talus slope of its own debris as might be supposed. Certain features, such as the long narrow reef-isthmus between Eleuthra and Cat islands, preclude such a mode of origin. This isthmus is about 20 miles long, but where crossed by the Expedition was less than a mile and a half wide. It is bounded on either side by steep reef-cliffs (Fig. 2). In such a structure any possible outward building of the reef laterally is limited, since the reef is only 1-1/2 miles wide, and it is unlikely that such a long narrow strip could have been built outward from either or both of its ends. Thus if upward building of the reef-material was responsible for this structure, it seems logical to believe it was also the most important factor in the formation of other parts of the platform.

Another strong point in favor of building up, rather than building out, is that the "reef-cliffs" extend to a depth of two or three thousand feet below sea-level. They may not be vertical slopes, but they are certainly far too steep to be talus-slopes. If the reef were to build out over its own talus, then that talus must reach up to the place where reef building is going on, within a couple of hundred feet of the surface at most. In the varicus places where the "reef-cliffs" were studied, talus-slopes, if present at all, were below 400 fathoms.

Age of the valleys

At the present time few data are available to determine the time of emergence and erosion of the valleys. Last summer a diamond-drill hole was started on the south shore of New Providence Island. A depth of 395 feet was reached in the calcareous "reef"-material. Fossils taken from the core were determined by Dr. Pilsbry as being definitely of Pliocene age. The valleys are older than the "reef"-material, thus making them at least Pre-Pliocene. There is no reason to suppose that they may not be very old geologically. With a more detailed study of the structural control, the age of the structures may perhaps be determined, thus giving a lower limit for the age of the valleys. Deeper drilling into the reef-material may also be able to move back the upper limit; and, if the reef-material were drilled through, information might be obtained as to the age of the rocks in which the valleys are cut.

Princeton University,
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INVESTIGATIONS OF SUBMARINE VALLEYS

F. P. Shepard

The introduction of echo-sounding and the use of bombs to determine positions have made it possible to discover many new submarine valleys and to develop their configuration with a speed and accuracy undreamed of hitherto. Prior to 1930 there was almost no suspicion of the presence of submarine valleys off the New England coast. The old charts showed an essentially straight 100-fathom curve along this area, yet within the last three years 27 true canyons have been found cutting into the

outer edge of the continental shelf all having depths of more than 1,000 feet below their marginal zones and attaining depths below sea-level of over a mile. Three of these canyons discovered last summer have walls rising from 2,500 to 4,000 feet above their floors. Where these canyons have been charted in the greatest detail it becomes evident that they have the characteristics of the great river-cut canyons of western United States (Fig. 1). They are also comparable with many of the larger submarine canyons which have been charted off the Pacific coast.

The recent surveys have indicated that at least many of the valleys are the product of river-erosion evidently at a time when the present submerged continental margins were well above sea-level. There are reasons to believe, as I have suggested elsewhere (F. P. Shepard, "Submarine valleys," Geog. Review, v. 23, 77-89), that the uplifts were during remote periods, and that the drowned canyons have remained unfilled only because great landslides periodically remove the fine sediment from the troughs. These ideas are by no means firmly established. The shapes of the valleys appear to indicate a fluvial origin since they have in general the sinuosity, the dendritic tributaries, the proper directions in relation to slopes, and the outward grading bases which characterize river-valleys and do not characterize elongate depressions of other origin. Yet these deep canyons are found off all the continents, and the idea that there has been such a wholesale uplift of continental margins is somewhat startling. We should certainly consider most carefully every other possible mode of origin of the canyons, and evidence should be sought which would either reject or more firmly entrench the idea of fluvial origin.

Fig. 1

Methods of investigation

To obtain new evidence concerning the origin of the submarine valleys, something besides the routine charting-methods employed by governmental surveys is necessary. Research vessels or private yachts could be used to attack the problem by a variety of methods.

Current-meters--In order to see whether waves and currents are important in excavating or maintaining the valleys, current-meters could be used. If these meters could be anchored along the base of certain valleys with a recording-device so as to obtain data both on currents of continuous operation and on currents produced by storms or special tidal conditions, it should be possible to develop some understanding of the importance of these present-day influences.

Study of the topography--The surveys of submarine valleys by echo-soundings are highly practical, particularly in deep water, but they are subject to the error of giving the distance to the nearest reflecting surface of the bottom rather than the true depths. These inaccuracies are important where there are steep slopes, and even with the application of slope-corrections the result is somewhat in doubt. It seems inadvisable to use vertical-cast soundings in deep water since they are both inaccurate and consume too much time. However, in the shoaler portions of the submarine valleys vertical casts could be used to great advantage. If located accurately they

could be made to show the true configuration of the bottom. An intensive survey of a small area using buoys for accurate position-finding should be very productive of information.

The tributaries of a river-valley system generally enter the main valley with graded slopes. It would be interesting to see if this relation exists between tributaries and main channels in submarine valleys. The valley-walls on the outside of curves in river-valleys are commonly steeper than those on the inside. Echo-soundings could be employed to find whether submarine valleys possessed the same characteristic. The floors of river-canyons are usually limited in width to the width of the stream-channel. On the other hand, steep-walled fault-valleys commonly have broad bases. Also at the foot of the fault-scarps which bound fault-valleys depressions or rifts are found commonly. Closely spaced vertical-cast soundings could be employed to see whether the bases of the submarine valleys appear to show the characteristics of either of these types of valleys. Echo-soundings could be used to make an examination of the nature of the changes in course of the submarine valleys. Abrupt bends with straight courses between would suggest either direct or indirect fault-control, while sinuous curving-trends would suggest a river-valley origin. Also the heads of the valleys should be sounded to show what relation they bear to the flat continental shelf inside. In the case of the submarine valley off the Hudson, it would be most interesting to determine the relation between the outer deep, steep-walled canyon and the inner shoal-depression which runs across the continental shelf. This case of the Hudson appears to be the only one of its kind in the world.

Bottom-samples--Very few samples from submarine valleys have been studied, although notations of the bottom-character have been made by survey officers from a large number of these valleys. The floors appear to be covered with clay and silt for the most part, but there are many indications of coarse sediment and perhaps of rock bottom from the valley-walls. Cores of the bottom-materials should be obtained to see if there are indications of changing conditions in the upper few feet of the valley-fills. The use of a geological dredge like that employed by the geological work of the Pourquoi Pas in the English Channel (L. Dangeard, "Geologie Sousmarine de la Manche," Ann. Inst. Oceanogr., Tome 6, fasc. 1, 1928) should make it possible to obtain fragments of rock from the steeper portions of the canyon-sides. There is strong presumptive evidence of the existence of solid rock in these places. Such specimens might be of great value in delimiting the age of the canyons. Also the obtaining of substantial evidence of rock-bottom on the continental slopes would tend to confirm the idea that the continental shelves are a product of erosion rather than great piles of sediment built out from the lands. Incidentally some data regarding the stratigraphy of the rock underlying the shelf might be obtained.

It would also be interesting to determine the nature of present-day sedimentation within the submarine valleys. Sediment-traps like those used by Raymond and Stetson (P. E. Raymond and H. C. Stetson, Science, v. 73, 105-106, 1931) could be placed along the base of certain submarine valleys to see what sort of material is being transported along the bottom at different places.

Evidence concerning submarine landslides

The evidence which suggests that submarine landslides periodically reopen the submarine valleys also needs verification. The deepening of Sagami Bay at the time of the great Japanese earthquake of 1923 appears very probable and was evidently due to a landslide as it was too great to be due to sudden faulting (F. P. Shepard, "Depth changes in Sagami Bay during the great Japanese earthquake," J. Geol., v. 41, No. 3, 1933). Other cases such as those along the east coast of North America at the time of the Grand Banks earthquake are less certainly established. In any event it would be much more significant if some exact depths and locations could be obtained along the axes of certain submarine valleys where slopes are fairly steep, and where earthquakes are common. Resurveys after earthquakes would show whether or not real modifications had occurred. While the recent Long Beach earthquake was not very severe, except in its effects on poorly constructed buildings, it may have dislodged sediments from the submarine valleys along this coast. Since the previous surveys have been fairly complete, a resurvey here would show changes if they had been of a pronounced character.

Investigation of changes through landsliding is highly practical work. If it is found that these changes are quite common after earthquakes, it will be necessary to

rechart the sea-floor in the area adjoining the epicenters of all great submarine earthquakes. A real danger to navigation might develop through the extension of heads of submarine valleys well towards shore by great landslides. A good start could be made by rechecking the area off Long Beach.

Evidence of landslides might be found from an examination of the topography at the base of the steeply sloping portions of valley-floors. It is at these places that one would expect to find accumulations of landslide-debris forming hummocks and mounds. In many places the depths of the outer portions of the valleys are so great that it would be difficult to obtain this information even by echo-soundings. It might be worth looking for evidence along the coast of Southern California where the submarine valleys do not appear to have attained great depth. The original survey-charts near Point Hueneme, California, show some indications of hills outside of the submarine valleys, which may have been caused by landslide-debris.

Cores taken from the bottom of the submarine valleys in places where the outward slope shows a decrease or a reversal might bring up contorted strata suggestive of landsliding. Also the inclusion of foreign material in a mud core would suggest landsliding. Samples from the ocean-floor in the outer portions of the submarine valleys might bring to light organic material which was well out of its present habitat, but of recent origin. This would also suggest landsliding as a means of bringing the material to its present location.

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MONTHLY SEQUENCE OF SEA-SURFACE TEMPERATURE ON THE NEW YORK-SAN JUAN STEAMSHIP ROUTE

E. Monroe Harwood and Charles F. Brooks

Since April, 1926, the steamship Coamo of the Puerto Rico Line, New York to San Juan, has carried for the United States Weather Bureau a Negretti and Zambra sea-water thermograph, recording surface-temperatures at the depth of the ship's sea-water intake. With but few interruptions it has produced a continuous record of surface-temperature for each of its weekly passages, providing a fairly complete picture of the march of temperature in the ocean-surface along its route.

The Coamo thermograms have been studied and charted at the Woods Hole Oceanographic Institution and at Blue Hill Meteorological Observatory of Harvard University under the direction of Charles F. Brooks. By means of the charted temperatures of this and other steamship lines, the area from New York to San Juan has been divided into six regions of different characteristics and varying size (Fig. 1). These are the same as the regions discussed by Church a year ago (Trans. Amer. Geophys. Union, 13th annual meeting, 244-249, 1932) except that (1) his very narrow "Upwelling-Zone" just north of the "Cold Wall" and his adjoining "Cool-Water" region have been combined into a "Slope-Water" division, (2) his "Warm Area" has been renamed "Central-Atlantic Water," and (3), beyond the limit of his study, another zone, "Antilles Water," has been added.

The Coastal Water extends from the land to the edge of the continental shelf at the 100-fathom line, about 125 miles on the New York- San Juan Line. The Inner Zone, taken as 30 miles wide, has an annual temperature of 12°5 C, ranging from an average of 3°1 in February to 22°8 in August--a difference of 19°7. A Middle Zone, 65 miles wide, is but slightly warmer, 12°7 for the year; February's average is 3°9 and that of August, 22°6--an annual range of 18°7. The Outer Zone, 30 miles wide, has an annual mean of 13°4, rising from a minimum monthly mean of 5°3 in February to a maximum of 23°1 in August--a range of 17°8. As might be expected, the range of the innermost coastal-water is greatest. Examination of those instances when a marked change of temperature occurred from one week to the next indicates that changes in the surface-temperature of the general coastal-belt are first noted in the innermost strip, and appear successively in the middle and outermost parts of the belt. These changes and their progress come frequently, but are not evident in the monthly tabulation. Coastal-Water temperatures vary noticeably from the average. In general, during the

five-year period 1927-1932, Coastal-Water departures have agreed with air-temperature departures of corresponding months at Blue Hill Observatory, Hyde Park, Massachusetts (see Fig. 2).

From the Coastal Water, the Coamo passes into the Slope-Water, 120 miles wide at this crossing, extending from the edge of the continental shelf to the Cold Wall, north of the Gulf Stream--the name has been used by C. O. Iselin to denote deeper waters in the same general region. The mean annual temperature is 18°.6 and the mean annual range

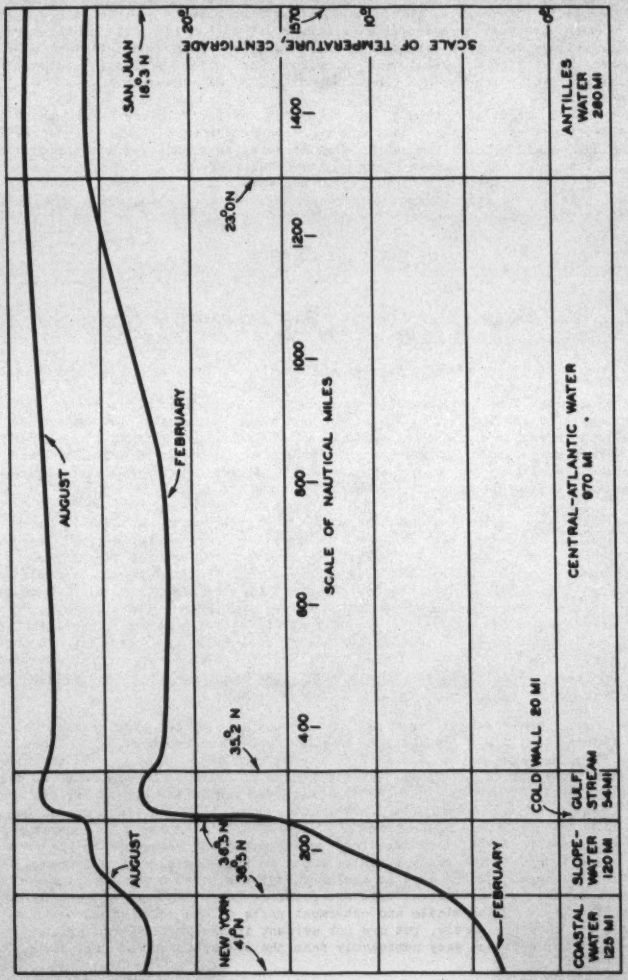


Fig. 1--Average sea-water temperature, Puerto Rico Line, 1927-32

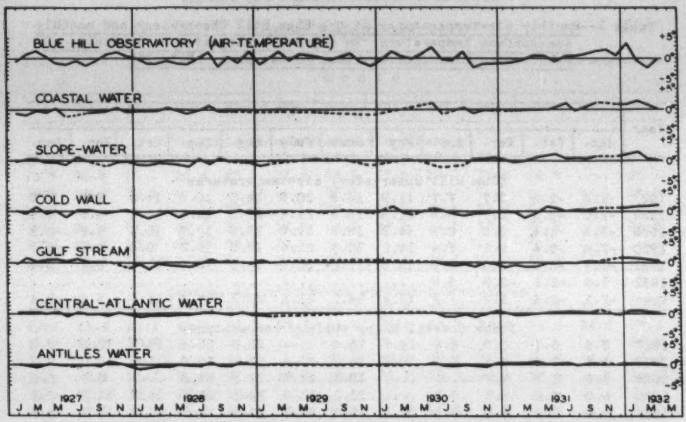


Fig. 2--Monthly surface-temperature departures in degrees Centigrade, Puerto Rico Line, New York to San Juan, 1927-32

15°.4, from 10°.2 in February to 25°.6 in August. Its departures are nearly as large as those of the Coastal Water, but do not show the same correspondence to the Blue Hill air-temperature departures. The width is quite constant, varying not more than 40 miles, usually much less.

Immediately north of the Gulf Stream, the thermograph-trace takes a sudden rise within a short space of time and within an average distance of 20 miles. The rise is 10° or more in winter but only about 3° in summer. This region has been called the Cold Wall. It partakes of the characteristics of both of its neighbors, and in its narrow width affords a change from the cool Slope-Water on the north to the constantly warm Gulf Stream on the south. The mean annual temperature is 21°.7, with the maximum, 26°.6, in August and the minimum, 17°.5, in April--an annual range of 9°.1. Departures of the monthly mean temperature of the Cold Wall are smaller than in either of the two preceding regions. In April 1931, however, it was as great as 1°.5. The width is fairly constant, seldom varying more than 10 miles from its average width of 20 miles, but occasionally changing more, with the occurrence of fingering of warm and cold water, or incursions of Gulf Stream water into the Slope-Water. Generally, however, it follows the same course, as a narrow belt, immediately north of the Gulf Stream.

At the top of the sudden rise of temperature in the Cold Wall the thermograph-trace flattens out in the Gulf Stream, at this point 53.7 miles wide on the average. The mean annual temperature is 25°.2, the annual range is 5°.8, the maximum monthly mean is 28°.3 in August, and the minimum is 22°.5 in February. While the average width during three years (1929-32) varied from 43.3 miles in September to 65.2 miles in April, the short record shows no seasonal change in width. The variations seem to be erratic. During 1929, 1930, and 1931, the width of the Gulf Stream tended to increase slightly, but the first four months of 1932 showed a slight decrease, these changes covering less than six miles. Flanked by belts of different temperature, the Gulf Stream is subject to considerable influence in both its warmth and its width, and, were it not for its constant motion, it would probably be more noticeably affected.

The Gulf Stream departures plotted against those of air-temperature at Blue Hill Observatory seem to show, in the five years, a positive relation. Breaks in the sea-temperature record make comparison for the whole period impossible, but comparison of peaks in the curve for Blue Hill with peaks in that for the Gulf Stream seems to show that these come generally in the same month, and, in two cases, in succeeding months. Comparison of weekly departures might show the relation more accurately, but the monthly figures are sufficient to suggest that a relation exists between these widely separated regions.

Table 1--Monthly air-temperatures at the Blue Hill Observatory and monthly sea-surface temperatures in degrees Centigrade on steamships of Puerto Rico Line from New York to San Juan, 1927-1932

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Blue Hill Observatory air-temperatures												
1927	-2.8	-1.3	3.7	7.7	11.9	16.8	20.9	18.5	16.8	12.8	7.5	0.2
1928	-2.0	-3.3	0.7	6.5	11.8	16.9	21.4	22.1	15.2	12.1	4.9	1.4
1929	-3.8	-2.4	3.3	6.9	14.2	18.9	21.6	19.8	17.7	10.2	4.8	-2.2
1930	-2.6	-0.4	2.1	7.4	14.2	20.8	21.4	19.8	19.2	9.3	4.5	-1.7
1931	-3.3	-3.3	1.3	7.9	13.8	17.6	22.3	20.9	18.4	13.4	8.1	0.4
1932	1.9	-2.8	-0.3	6.9	....	....	....	....	....	....	....	....
Mean	-2.1	-2.3	1.8	7.2	13.2	18.2	21.5	20.2	17.4	11.6	5.9	-0.4
Inner Coastal Water surface-temperatures												
1927	3.6	3.1	3.9	6.1	11.7	15.6	....	22.2	20.6	18.3	12.8	7.8
1928	3.3	2.2	3.3	5.3	10.6	15.6	21.1	23.9	20.6	17.8	10.0	6.9
1929	3.3	1.7	1.7	....	....	19.4	21.9	22.2	23.3	....	8.6	5.6
1930	5.0	3.9	6.1	8.3	....	21.1	21.1	22.2	22.2	16.7	11.1	6.1
1931	3.3	2.8	5.0	8.3	11.1	16.9	23.6	23.3	22.2	20.0	13.1	8.9
1932	7.2	5.0	5.0	6.7	....	....	....	....	....	....	....	....
Mean	4.3	3.1	4.2	6.9	11.1	18.1	21.9	22.8	21.8	18.2	11.1	7.1
Middle Coastal Water surface-temperatures												
1927	4.3	3.7	4.7	6.9	11.8	16.1	21.7	21.6	20.0	17.9	12.1	7.1
1928	4.3	3.7	4.1	6.4	11.3	16.9	21.5	23.7	20.4	16.8	10.0	8.1
1929	3.6	1.9	3.1	....	....	19.1	21.7	21.7	23.3	....	9.2	6.4
1930	4.4	5.0	6.1	8.3	....	20.0	21.2	22.9	22.2	17.1	10.8	6.5
1931	3.7	3.1	4.7	7.2	11.1	16.9	24.1	23.2	22.6	19.1	12.8	9.6
1932	7.3	5.9	5.7	7.1	....	....	....	....	....	....	....	....
Mean	4.6	3.9	4.7	7.2	11.4	18.2	22.0	22.6	21.7	17.7	11.0	7.2
Outer Coastal Water surface-temperatures												
1927	3.9	3.3	5.0	6.7	11.1	15.6	22.8	22.8	20.6	18.1	13.3	10.3
1928	6.7	5.8	5.6	5.6	11.1	17.8	21.4	23.3	18.9	17.8	11.1	10.3
1929	7.2	3.9	4.7	....	....	20.3	21.7	22.2	22.2	....	11.1	8.9
1930	6.7	6.1	6.1	8.3	....	20.0	22.2	23.3	22.2	18.3	12.8	9.4
1931	6.1	5.6	5.3	7.8	11.1	17.2	23.3	23.9	22.2	19.4	13.9	11.1
1932	9.2	7.2	6.7	6.9	....	....	....	....	....	....	....	....
Mean	6.6	5.3	5.6	7.1	11.1	18.2	22.3	23.1	21.2	18.4	12.4	10.0
Slope-Water surface-temperatures												
1927	11.3	10.6	10.6	10.3	12.6	17.9	23.4	25.3	....	20.2	15.9	13.9
1928	10.6	9.1	9.8	9.8	11.8	17.3	22.8	24.8	24.9	21.1	....	13.5
1929	10.1	9.4	....	....	....	19.0	22.6	....	24.6	....	....	12.9
1930	....	9.9	....	10.8	....	....	20.8	....	23.4	21.9	16.7	14.8
1931	11.6	9.9	10.3	11.4	14.3	20.9	23.2	26.5	25.0	22.6	....	15.1
1932	13.1	12.4	10.9	11.1	....	....	....	....	....	....	....	....
Mean	11.4	10.2	10.4	10.7	12.9	18.8	22.6	26.6	24.5	21.4	16.3	14.1
Cold Wall surface-temperature												
1927	18.4	17.9	18.7	17.3	19.8	22.2	26.6	27.2	26.7	24.9	21.9	20.4
1928	17.8	16.4	17.1	17.2	18.4	22.8	25.7	26.1	26.8	24.9	21.8	19.6
1929	17.9	17.7	....	....	....	23.4	25.7	....	26.8	....	....	19.5
1930	....	19.2	17.3	16.9	....	24.2	26.2	26.0	25.6	24.4	21.3	19.8
1931	18.2	17.8	16.2	17.0	21.2	24.3	26.2	27.1	26.7	25.7	....	20.9
1932	19.2	19.2	19.0	19.1	....	....	....	....	....	....	....	....
Mean	18.3	18.0	17.7	17.5	19.8	23.4	26.1	26.6	26.5	25.0	21.7	20.1

Table 1--Continued

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Gulf Stream surface-temperatures												
1927	22.7	23.6	23.4	24.1	25.3	27.1	28.7	28.6	28.4	26.9	....	22.8
1928	22.4	21.1	22.8	22.8	23.8	25.8	27.5	29.0	28.2	26.9	....	24.1
1929	23.3	22.5	....	....	....	27.1	....	....	....	....	....	24.6
1930	....	....	....	23.7	....	27.1	27.3	27.5	27.6	25.6	24.4	23.4
1931	21.8	21.8	22.0	22.4	24.3	26.4	27.8	28.2	28.2	26.9	....	25.3
1932	24.1	23.6	23.7	23.8	....	....	....	....	....	....	....	....
Mean	22.8	22.5	23.0	23.4	24.4	26.7	27.8	28.3	28.1	26.6	24.4	24.1
Central-Atlantic Water surface-temperatures												
1927	22.5	21.9	21.8	22.0	23.5	25.4	27.4	27.9	28.3	26.2	24.4	23.6
1928	21.4	21.1	21.1	21.1	22.7	25.4	27.1	28.3	28.3	26.4	24.6	23.4
1929	21.9	20.9	....	....	....	....	....	....	....	....	....	23.6
1930	....	....	....	22.1	....	25.8	26.2	27.1	27.7	25.8	24.3	23.6
1931	22.4	21.1	21.1	21.7	23.2	25.6	27.1	28.3	28.4	27.4	....	24.6
1932	23.2	22.4	21.9	21.9	....	....	....	....	....	....	....	....
Mean	22.3	21.5	31.4	21.8	23.1	25.6	26.9	27.9	28.2	26.3	24.4	23.8
Antilles Water surface-temperatures												
1927	24.4	25.4	25.4	26.1	27.1	27.3	....	28.9	28.8	29.5	28.4	26.7
1928	25.1	25.1	25.3	25.4	26.8	27.5	28.2	29.3	28.8	28.6	28.2	....
1929	....	25.7	....	....	....	27.4	....	....	....	....	....	26.9
1930	....	....	....	25.7	....	27.9	28.1	28.5	28.8	28.4	27.6	27.3
1931	26.4	26.0	26.1	26.7	27.2	27.8	28.7	28.9	29.1	29.0	....	27.2
1932	26.3	25.8	26.0	26.1	....	....	....	....	....	....	....	....
Mean	25.6	25.6	25.7	26.0	27.0	27.6	28.3	28.9	28.9	28.9	28.1	27.0

Table 2--Monthly departures in degrees Centigrade from 5-year means of air-temperatures at the Blue Hill Observatory and of sea-surface temperatures on steamships of Puerto Rico Line from New York to San Juan, 1927-1932

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Blue Hill Observatory air-temperature departures												
1927	-0.7	+1.0	+1.9	+0.5	-1.2	-1.4	-0.6	-1.7	-0.6	+1.2	+1.6	+0.6
1928	+0.1	-1.0	-1.1	-0.7	-1.3	-1.3	-0.1	+1.8	-2.3	+0.5	-1.1	+1.8
1929	-1.7	-0.2	+1.5	-0.3	+1.0	+0.7	+0.1	-0.4	+0.3	-1.3	-1.1	-1.8
1930	-0.5	+1.9	+0.3	+0.2	+1.0	+2.6	-0.1	-0.4	+1.7	-2.3	-1.4	-1.3
1931	-1.2	-1.0	-0.5	+0.7	+0.7	-0.6	+0.8	+0.7	+0.9	+1.8	+2.1	+0.8
1932	+4.1	-0.6	-2.1	-0.3	....	....	....	....	....	....	....	....
Inner Coastal Water surface-temperature departures												
1927	-0.7	-0.1	-0.3	-0.8	+0.6	-2.6	0.0	-0.6	-1.2	+0.1	+1.7	+0.7
1928	-1.0	-0.9	-0.8	-1.7	-0.6	-2.6	-0.8	+1.1	-1.2	-0.4	-1.1	-0.2
1929	-1.0	-1.4	-2.5	....	....	+1.3	0.0	-0.6	+1.6	....	-2.9	-1.5
1930	+0.7	+0.8	+1.9	+1.4	....	+3.0	-0.8	-0.6	+0.4	-1.5	0.0	-1.0
1931	-1.0	-0.3	+0.8	+1.4	0.0	+0.8	+1.7	+0.4	+0.4	+1.8	+2.0	+1.8
1932	+2.9	+1.9	+0.8	-0.3	....	....	....	....	....	....	....	....

Note: The mean yearly air-temperature departures at Blue Hill Observatory are: 1927, +0°1; 1928, -0°3; 1929, -0°3; 1930, +0°2; and 1931, +0°4.

Table 2--Continued

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Middle Coastal Water surface-temperature departures												
1927	-0.3	-0.2	0.0	-0.3	+0.4	-2.1	-0.3	-1.0	-1.7	+0.2	+1.1	-0.1
1928	-0.3	-0.2	-0.6	-0.8	-0.1	-1.3	-0.5	+1.1	-1.3	-0.9	-1.0	+0.9
1929	-1.0	-2.0	-1.6	....	....	+0.9	-0.3	-0.9	+1.6	....	-1.8	-0.8
1930	-0.2	+1.1	+1.4	+1.1	....	+1.8	-0.8	+0.3	+0.5	-0.6	-0.2	-0.7
1931	-0.9	-0.8	0.0	0.0	-0.3	+0.7	+2.1	+0.6	-0.9	+1.4	+1.8	+2.4
1932	+2.7	+2.0	+1.0	-0.1	....	....	....	....	....	....	....	....
Outer Coastal Water surface-temperature departures												
1927	-2.7	-2.0	-0.6	-0.4	0.0	-2.6	+0.5	-0.3	-0.6	-0.3	+0.9	+0.3
1928	+0.1	+0.5	0.0	-1.5	0.0	-0.4	-0.9	+0.2	-2.3	-0.6	-1.3	+0.3
1929	+0.6	-1.4	-0.9	....	....	+2.1	-0.6	-0.9	+1.0	....	-1.3	-1.1
1930	+0.1	+0.8	+0.5	+1.2	....	+1.8	-0.1	+0.2	+1.0	-0.1	+0.4	-0.6
1931	-0.5	+0.3	-0.3	+0.7	0.0	-1.0	+1.0	+0.8	+1.0	+1.0	+1.5	+1.1
1932	+2.6	+1.9	+1.1	-0.2	....	....	....	....	....	....	....	....
Slope-Water surface-temperature departures												
1927	-0.1	+0.3	+0.2	-0.4	-0.3	-0.9	+0.9	-0.2	....	-1.3	-0.4	-0.1
1928	-0.8	-1.1	-0.6	-0.9	-1.1	-1.5	+0.3	-0.7	+0.4	-0.4	....	-0.6
1929	-1.3	-0.8	....	....	....	+0.2	+0.1	....	+0.1	....	....	-1.2
1930	....	-0.3	....	+0.2	....	....	-1.7	....	-1.1	+0.5	+0.4	+0.7
1931	+0.2	-0.3	-0.1	+0.8	+1.4	+2.1	+0.6	+0.9	+0.5	+1.1	....	+1.1
1932	+1.7	+2.2	+0.5	+0.4	....	....	....	....	....	....	....	....
Cold Wall surface-temperature departures												
1927	+0.1	-0.1	+1.1	-0.2	+0.1	-1.2	+0.5	+0.6	+0.2	-0.1	+0.2	+0.4
1928	-0.5	-1.6	-0.6	-0.3	-1.4	-0.3	-0.4	-0.5	+0.3	-0.1	+0.1	-0.4
1929	-0.3	-0.3	....	....	....	0.0	-0.4	....	+0.3	....	....	-0.5
1930	....	+1.2	-0.3	-0.6	....	+0.8	+0.1	-0.5	-0.9	-0.6	-0.4	-0.2
1931	-0.1	-0.2	-1.5	-0.5	+1.4	+0.8	+0.1	+0.5	+0.2	+0.7	....	+0.9
1932	+0.9	+1.2	+1.3	+1.6	....	....	....	....	....	....	....	....
Gulf Stream surface-temperature departures												
1927	-0.1	+1.1	+0.4	+0.8	+0.9	+0.4	+0.9	+0.3	+0.3	+0.3	....	-1.3
1928	-0.4	-1.4	-0.2	-0.6	-0.7	-0.9	-0.3	+0.7	+0.1	+0.3	....	-0.1
1929	+0.5	0.0	....	....	....	+0.4	....	....	....	....	....	+0.4
1930	....	....	....	+0.3	....	+0.4	-0.5	-0.8	-0.5	-1.0	-0.0	-0.2
1931	-1.1	-0.7	-1.0	-0.9	-0.2	-0.3	0.0	-0.1	+0.1	+0.3	....	+1.2
1932	+1.2	+1.1	+0.7	+0.4	....	....	....	....	....	....	....	....
Central-Atlantic Water surface-temperature departures												
1927	+0.2	+0.4	+0.4	+0.2	+0.4	-0.2	+0.4	0.0	+0.1	-0.3	0.0	-0.2
1928	-0.9	-0.4	-0.4	-0.7	-0.4	-0.2	+0.1	+0.4	+0.2	-0.1	+0.2	-0.4
1929	-0.4	-0.6	....	....	....	....	....	....	....	....	....	-0.2
1930	....	....	....	+0.3	....	+0.3	-0.8	-0.8	-0.4	-0.7	-0.1	-0.2
1931	+0.1	-0.4	-0.4	-0.1	+0.1	+0.1	+0.2	+0.4	+0.3	+0.9	....	+0.8
1932	+0.9	+0.9	+0.5	+0.2	....	....	....	....	....	....	....	....
Antilles Water surface-temperature departures												
1927	+0.1	-0.2	-0.3	+0.1	+0.1	-0.3	....	0.0	-0.1	+0.6	+0.3	-0.3
1928	-0.8	-0.6	-0.4	-0.6	-0.2	-0.1	-0.2	+0.4	-0.1	-0.3	+0.1	....
1929	....	+0.1	....	....	....	-0.2	....	....	....	....	....	-0.1
1930	....	....	....	-0.3	....	+0.3	-0.2	-0.4	-0.1	-0.5	-0.5	+0.3
1931	+0.4	+0.4	+0.4	+0.7	+0.2	+0.2	+0.4	0.0	+0.2	+0.1	....	+0.2
1932	+0.3	+0.2	+0.3	+0.1	....	....	....	....	....	....	....	....

CORRECTED TABLE TO REPLACE TABLE 3, PAGE 179, TRANSACTIONS OF THE AMERICAN GEOPHYSICAL UNION, FOURTEENTH ANNUAL MEETING

Table 3--Widths in nautical miles of six temperature-divisions for route New York to San Juan of Puerto Rico Line, 1929-1932

Year	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	
						Coastal Water							
1929	125	128	128	...	...	114	118	...	118	...	117	118	121
1930	123	117	117	116	...	117	118	117	116	117	122	121	118
1931	118	117	117	117	117	117	117	116	117	116	123	117	117
1932	119	117	117	...	...	...	...	...	...	...	...	...	...
Mean	121	120	120	117	117	116	118	117	117	117	121	119	118
						Slope Water							
1929	65	93	97	...	...	...	102	...	132	...	111	103	101
1930	96	105	120	111	...	72	93	105	90	108	100	78	98
1931	102	75	118	150	155	139	106	141	139	147	100	97	122
1932	117	129	146	134	...	...	...	...	...	...	...	...	...
Mean	95	100	121	132	155	106	100	123	120	128	104	93	115
						Cold Wall							
1929	18	18	37	...	...	24	22	...	8	...	14	20	20
1930	15	8	32	18	...	42	17	7	30	15	30	42	23
1931	21	7	26	14	14	20	32	22	23	13	35	40	22
1932	20	24	21	25	...	...	...	...	...	...	...	...	...
Mean	19	14	29	19	14	29	24	15	20	14	26	34	21
						Gulf Stream							
1929	55	51	47	...	...	41	40	...	43	...	31	37	43
1930	47	39	42	66	...	32	70	36	30	42	41	60	46
1931	45	34	35	52	52	59	42	80	45	63	50	37	50
1932	49	41	39	50	...	...	...	...	...	...	...	...	...
Mean	49	41	41	56	52	44	51	58	39	53	41	45	48
						Central-Atlantic Water							
1929	868	872	832	...	...	883	790	...	665	...	930	832	834
1930	967	894	840	898	...	825	757	720	898	797	840	807	840
1931	874	973	978	892	794	765	833	764	804	808	905	845	853
1932	802	867	808	795	...	...	...	...	...	...	...	...	...
Mean	878	902	832	862	794	824	793	742	789	803	892	828	828
						Antilles Water							
1929	253	220	240	...	...	268	263	...	384	...	195	267	261
1930	135	212	175	175	...	295	322	400	215	272	195	207	237
1931	216	178	109	122	240	285	226	257	257	233	222	246	216
1932	255	212	266	262	...	...	...	...	...	...	...	...	...
Mean	215	206	198	186	240	283	270	329	285	253	204	240	242

Note: All figures relating to widths in the text should be changed according to the distances given in this corrected Table.

Table 3--Widths in nautical miles of six temperature-divisions for route New York to San Juan of Puerto Rico Line, 1929-1932

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Coastal Water, width constant (by definition), 125 miles													
Slope-Water													
1929	70	100	115	...	...	94	110	...	150	...	124	117	110
1930	107	122	136	126	...	84	106	117	102	127	119	93	113
1931	117	85	134	173	177	140	119	160	159	170	113	115	138
1932	134	145	161	152	...	...	...	...	...	...	...	...	...
Mean	107	113	136	151	177	106	111	138	137	148	119	108	120
Cold Wall													
1929	20	20	15	...	...	17	25	...	10	...	15	22	18.0
1930	17	9	20	20	...	45	20	8	35	15	13	25	22.7
1931	22	10	11	16	14	22	18	24	16	15	30	17	17.9
1932	14	17	16	19	...	...	...	...	...	...	...	...	.....
Mean	18	14	15.5	18	14	28	21	16	20	15	19	21	18.8
Gulf Stream													
1929	64	60	55	...	...	54	42	...	50	...	37	43	50.8
1930	55	46	48	76.5	...	38	82	42	35	55	48	70	54.1
1931	57.5	41	41	61	60	75	57	71	45	72	58	38	56.4
1932	56	48	47	58	...	...	...	...	...	...	...	...	.....
Mean	58.1	48.7	47.7	65.2	60	55.8	60.3	56.5	43.3	63.5	47.7	50.5	54.8
Central-Atlantic Water													
1929	1000	1000	955	....	...	1015	975	...	778	...	1050	965	967
1930	1110	1035	1033	1027	...	990	881	845	1037	905	1005	1000	988
1931	1002	1115	1122	1048	924	890	1013	874	929	925	975	919	984
1932	937	996	932	900	...	....	....	...	....	...	....	....	...
Mean	1012	1036	1010	992	924	965	956	859	915	915	1010	987	970
Antilles Water													
1929	295	250	276	...	...	295	302	...	480	...	225	310	304
1930	155	245	203	200	...	340	370	465	250	360	247	235	279
1931	252	205	118	140	278	335	262	298	300	265	255	265	248
1932	320	235	286	302	...	...	...	...	...	...	...	...	...
Mean	255	234	221	214	278	323	311	381	343	312	242	270	279

South of the Gulf Stream, the Coamo steams through the western end of the broad Central-Atlantic Water, at this crossing 970 miles wide, with a mean temperature of 24°4 and a range of 6°8. Its maximum, 28°2, comes in September and its minimum, 21°4, in March. Central-Atlantic Water monthly departures are small, and seem to be larger in winter than in summer. With the fluctuating Gulf Stream on one side, and the poorly defined Antilles Water on the other, its width, like that of the Gulf Stream, varies erratically. Yearly averages of width, however, are quite constant, varying less than 25 miles from the average of 970 miles for the period from 1929 through April 1932. There is some indication of lesser widths in summer and of greater widths in winter.

The final stretch on the route to Puerto Rico, the Antilles Water, extends from the southern edge of the Central-Atlantic Water, about 280 miles to San Juan. The line separating the two divisions is poorly marked; the Antilles Water is distinguished only by a flattening of the thermograph-trace to almost a horizontal line. From this we may expect rather constant conditions, and we find the mean annual temperature to be 27°8, with the maximum, 28°9, coming in August or September and the minimum, 26°6, in February. The range is but 3°3. The monthly departures are the smallest of the six divisions, being, for the most part, almost imperceptible. They seem to be largest in winter or spring. With its northern boundary so poorly defined, the width of this area fluctuates considerably, the changes being generally

complementary to those of the Central-Atlantic Water. As noted in connection with the discussion of the Gulf Stream, the record suggests a relation between departures of this area and those of air-temperature at Blue Hill. The peaks of the sea-temperature curve come in the same month as, or in the month before, the corresponding ones in the Blue Hill record. In four positive peaks of temperature during 1927-1932, and five negative peaks, the three places, Antilles Water, Gulf Stream, and Blue Hill, show essential concurrence in the character of departures.

These monthly temperatures have value, in that they provide in fairly concise form the essential data, and although they do not permit consideration of the details, they suggest major changes. The western Atlantic, which washes our eastern shores, influences our climate here on the east coast. Knowledge of the ocean-temperatures, both at the surface and at greater depths may shed light on the seasonal variations of weather in temperate eastern North America.

Woods Hole Oceanographic Institution (Contribution No. 15),
Woods Hole, Massachusetts, and
Blue Hill Meteorological Observatory, Harvard University,
Hyde Park, Massachusetts

OCEANOGRAPHIC WORK OF THE HYDROGRAPHIC OFFICE AND THE UNITED STATES NAVY DURING THE PAST YEAR

W. R. Gherardi

The activities of the Hydrographic Office, United States Navy Department, and of the United States Navy during the past year in the fields of oceanography were briefly as follows.

Naval surveys--Under the direction of the Hydrographic Office three surveying-vessels conducted surveys of the high seas and foreign coasts for the further benefit of the United States Navy and the merchant marine.

The U.S.S. Nokomis completed the surveying of the coasts and coastal waters of the Island of Cuba, originally begun in 1899. In addition to the general chart of Cuba, 21 coastal charts and 56 harbor- or plan-charts have been published as the results of these surveys. These charts with the resulting revised Sailing Directions provide the mariner with accurate information of Cuban waters and coasts (Fig. 1).

Due to the reported grounding of several vessels in the vicinity of Mucaras Reef, Bahama Islands, and the apparent necessity of having better information as to the extent of shoal-water in that area and the circulation of waters between it and Cuba, the Hydrographic Office, with the consent of the British Government, directed the U.S.S. Nokomis to make investigations and surveys in those regions (Fig. 2).

The accompanying diagram illustrates the method used in expanding triangulation from Lobos Cay, Great Bahama Bank, and Cayo Confites, Cuba, both main triangulation-stations of the Cuban survey.

The results of the survey place the reef about one mile farther south and three-quarters of a mile farther west than previously charted. A deep-sea development of an area of 70 square miles southward of the reef failed to disclose any detached shoals.

In the Gulf of Panama, the U.S.S. Fulton, U.S.S. Hannibal, and U.S.S. Nokomis continued the survey of those waters, which was begun by the U.S.S. Niagara in 1928.

Aerial photography was employed in connection with all the surveys for detailed delineation of shore-lines and other topographic features.

Charts from United States Naval surveys--Nine new Hydrographic Office charts have been published during the year 1932 based upon original United States Naval surveys. They are: 1810, Maturin Bar and Approaches to Rio San Juan, Gulf of Paria, Venezuela; 1811, Rio San Juan, Gulf of Paria, Venezuela; 1882, Puerto Gibara, North Coast of Cuba; 1970, Puerto Padre, North Coast of Cuba; 2145, Island of Cuba; 2628, Punta Ma-

ternillos to Punta Lucrecia, North Coast of Cuba; 5165, Bahia Manati and Nuevos Grandes, North Coast of Cuba; 5166, Bahia Jururo, Bahia Bariay, and Bahia Vita, North Coast of Cuba; and 5167, Bahia Naranjo and Bahia Sama, North Coast of Cuba.

Sonic soundings obtained by United States Naval vessels--A tabulated list of sonic soundings taken by United States Naval vessels from January 1, 1931 to December 31, 1932, follows:

U.S.S. Concord, Cincinnati, and Omaha - While cruising over "Guardian Bank" obtained (by U.S.S. Concord) a shoal of 15 fathoms by lead in 9° 39' N at 87° 18' W, and 170 sonic soundings crossing 8° 31' N in 86° 55' W and 9° 45' N in 87° 30' W.

U.S.S. Omaha - 22 sonic soundings obtained while searching for a rock (reported 1907) in 24° 41' N and 116° 10' W.

U.S.S. Ramapo - Enroute San Pedro, California, to Manila, Philippine Islands, recorded 700 sonic soundings crossing 33° 26' N in 121° 44' W, 26° 55' 30" N in 179° 09' 30" W, and 17° 37' N in 134° 16' E.

U.S.S. Ramapo - 575 sonic soundings on return trip Manila, Philippine Islands, to San Pedro, California, crossing 21° 07' N in 124° 30' 30" E, 30° 00' 00" N in 174° 02' 30" E, and 38° 15' 00" N in 136° 11' 00" W.

U.S.S. Fulton - 1,500 sonic soundings obtained enroute Watling Island (San Salvador) crossing 24° N in 74° 30' W to Cape Maysi Light (20° 15' N, 74° 45' W).

U.S.S. Chewink and U.S. Sub. S-48 - On gravity-expedition in the West Indies and Caribbean Sea obtained 2,600 sonic and supersonic soundings crossing 19° 50' N in 75° 10' W, 17° 30' N in 77° 20' W, 19° 15' N in 81° 00' W, 22° 00' N in 77° 00' W, 25° 00' N in 77° 40' W, and 26° 40' N in 79° 30' W.

U.S.S. Chaumont - 12 fathometer-soundings taken over unsurveyed area in San Bernardino Straits, Philippine Islands, in 12° 48' N and 124° 31' 45" E.

U.S.S. Augusta, Chicago, Northampton, Pensacola, Chester, and Salt Lake City - While cruising over Guardian Bank obtained 320 sonic soundings in approximately 9° N and 87° W.

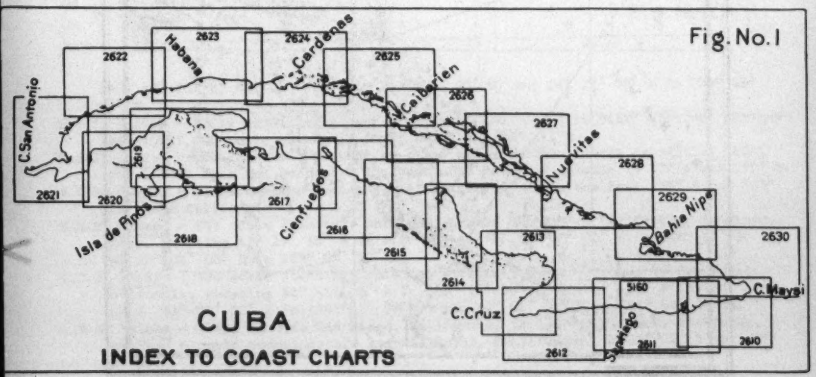
U.S.S. Hannibal - 231 sonic soundings taken enroute from Port of Spain, Trinidad, British West Indies, to Cristobal, Canal Zone, via Willemstad, Curaçao, crossing 10° 47' 30" N in 61° 54' 15" W, 12° 16' 15" N in 69° 37' 45" W, and 9° 28' 30" N in 79° 50' 30" W.

U.S.S. Ramapo - 207 sonic soundings obtained enroute San Pedro, California, to Manila, Philippine Islands, crossing 27° 59' 00" N in 178° 20' 00" W, 20° 54' 00" N in 159° 46' 00" E, and 15° 18' 00" N in 145° 40' 00" E.

U.S.S. Fulton - 55 supersonic soundings obtained enroute to the Gulf of Nicoya and passing over the area of obstructions reported southwest of Morro Puercos (Gulf of Panama) in approximately 7° 12' 26" N and 80° 17' 04" W.

U.S.S. Chaumont - 9 fathometer-soundings taken in San Bernardino Straits in 12° 50' 00" N and 124° 36' 00" E.

Fig. No. 1



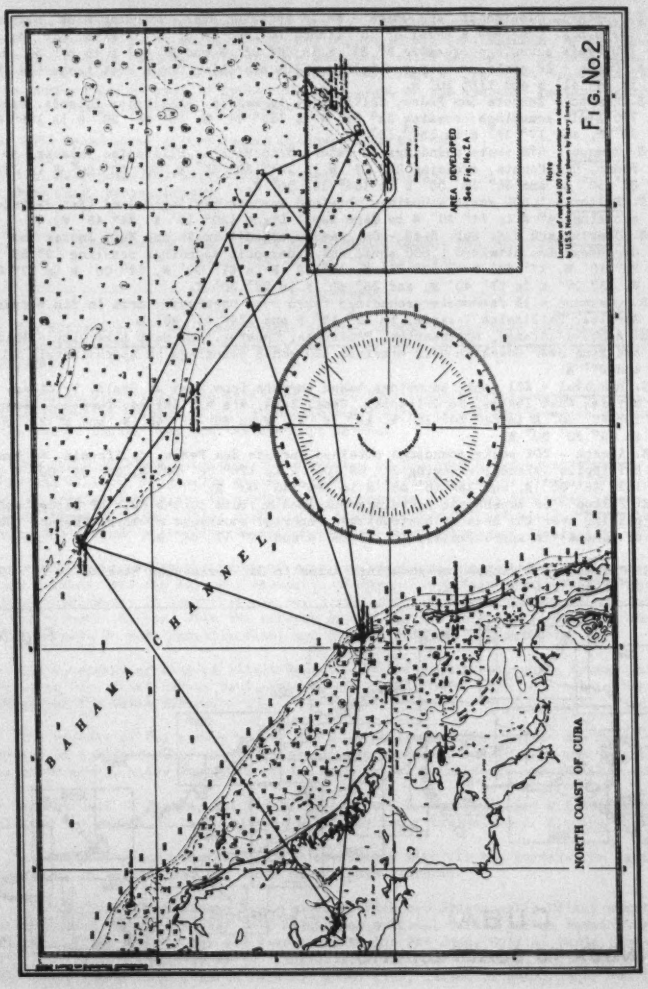
CUBA

INDEX TO COAST CHARTS

U.S.S. Marblehead - Reports a line of 58 supersonic soundings from Jicarita Light in 7° 12' 00" N and 81° 48' 00" W.

U.S.S. Marblehead - 70 sonic soundings taken south of the volcano lying near Punta Telmo (near Manzanillo) in 18° 19' 00" N and 103° 30' 00" W, and off Punta de Campos Light in 19° 01' 15" N and 104° 21' 00" W.

U.S.S. Ramapo - Enroute Manila, Philippine Islands to San Pedro, California, obtained 400 sonic soundings crossing 25° 08' 00" N in 129° 13' 00" E, 38° 36' 00" N in



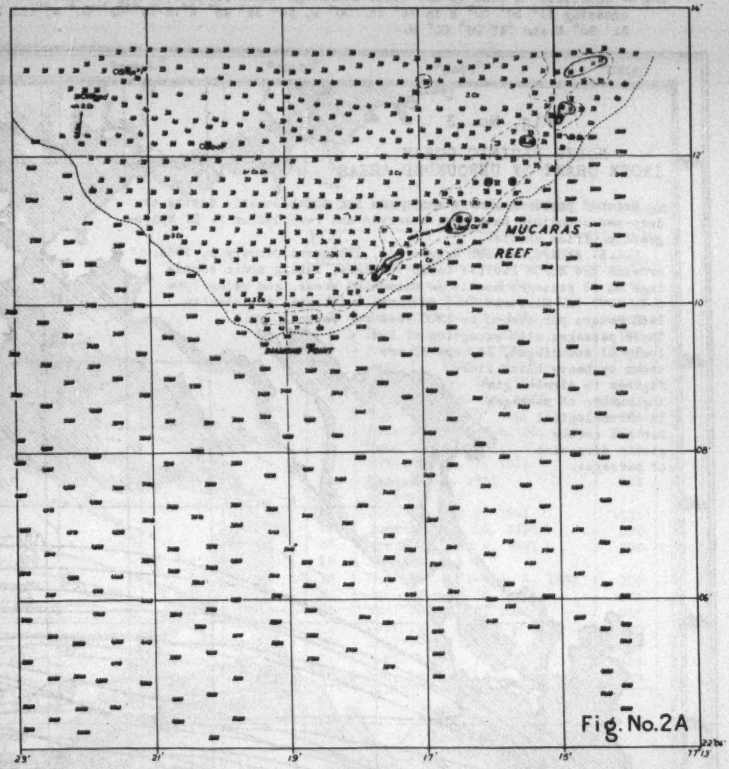


Fig. No.2A

159° 56' 00" E, 43° 10' 00" N in 161° 02' 00" W, and 36° 22' 00" N in 126° 32' 00" W.

U.S.S. Fulton - While executing a new survey over the "Guardian Bank" obtained approximately 17,000 sonic soundings in 9° 30' N and 86° 27' W.

U.S.S. Sirius - 135 fathometer-soundings taken while in the "Alaska Expedition 1932," near Unimak Pass and northward including the Pribilof Islands in 56° N and 170° W.

U.S.S. Neches - 21 fathometer-soundings in vicinity of Uncle Sam Bank (25° N and 113° W), Lower California.

U.S.S. Ramapo - 235 sonic soundings obtained enroute San Pedro, California, to Chefoo, China, crossing 30° 29' 30" N in 177° 48' 45" E, 30° 38' 00" N in 155° 27' 30" E, and 31° 03' 00" N in 139° 02' 30" E.

U.S.S. Ramapo - 324 sonic soundings obtained enroute Tsingtao, China, to San Pedro, California, crossing 32° 53' 04" N in 140° 16' 30" E, 40° 07' 00" N in 164° 47' 15" E, 41° 00' 00" N in 178° 58' 00" W, and 41° 01' 00" N in 143° 54' 30" W.

U.S.S. Patoka - While enroute San Diego, California, to Gulf of Fonseca, Nicaragua, obtained 4 sonic soundings off Amapala Point, El Salvador, in 13° 29' N and 90° 27' W.

U.S.S. Hannibal - A line of 150 sonic soundings taken enroute to Cape Maysi, Cuba, crossing 31° 30' 00" N in 76° 28' 00" W, 25° 35' 45" N in 75° 09' 00" W, and 21° 31' 30" N and 75° 06' 00" W.

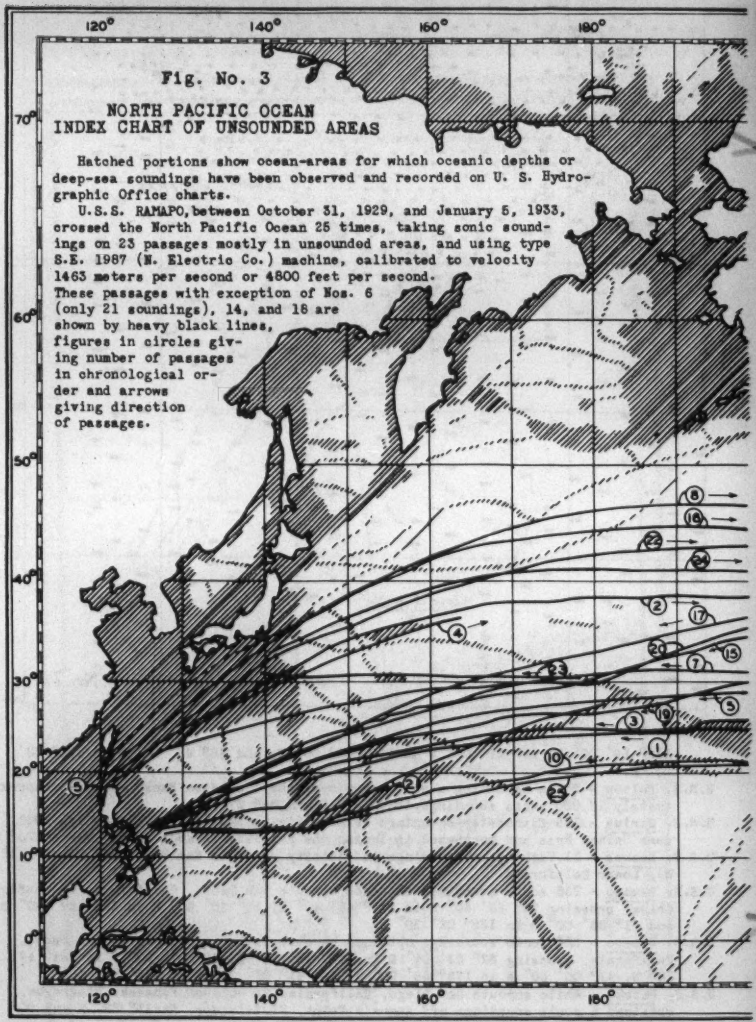

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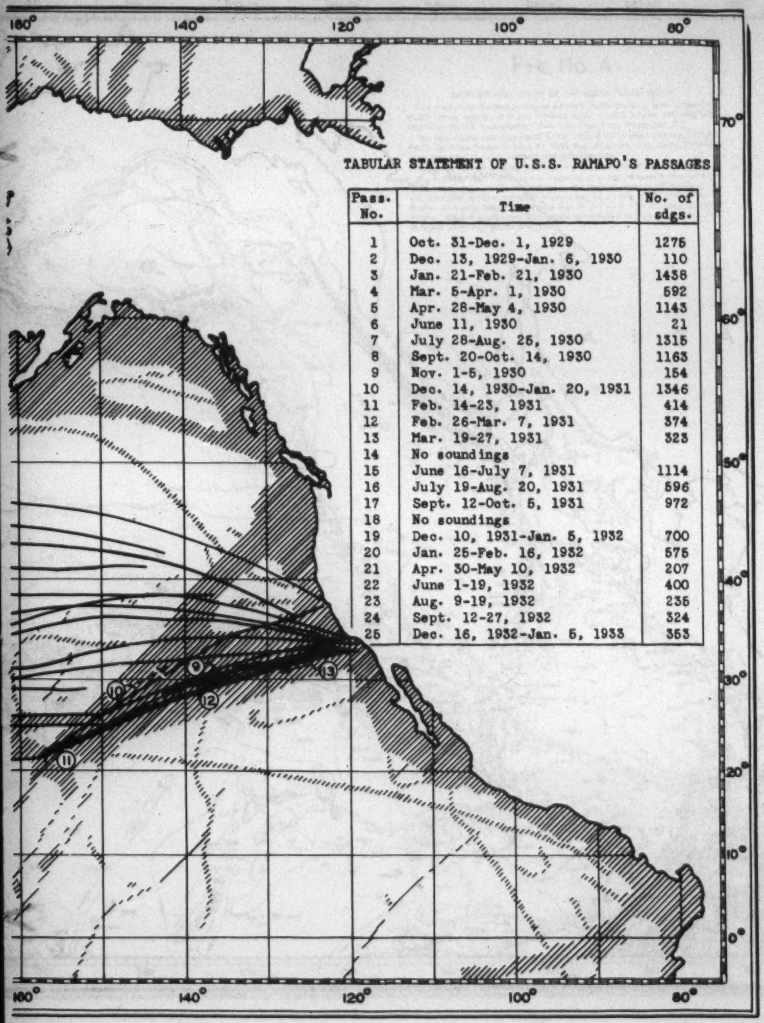
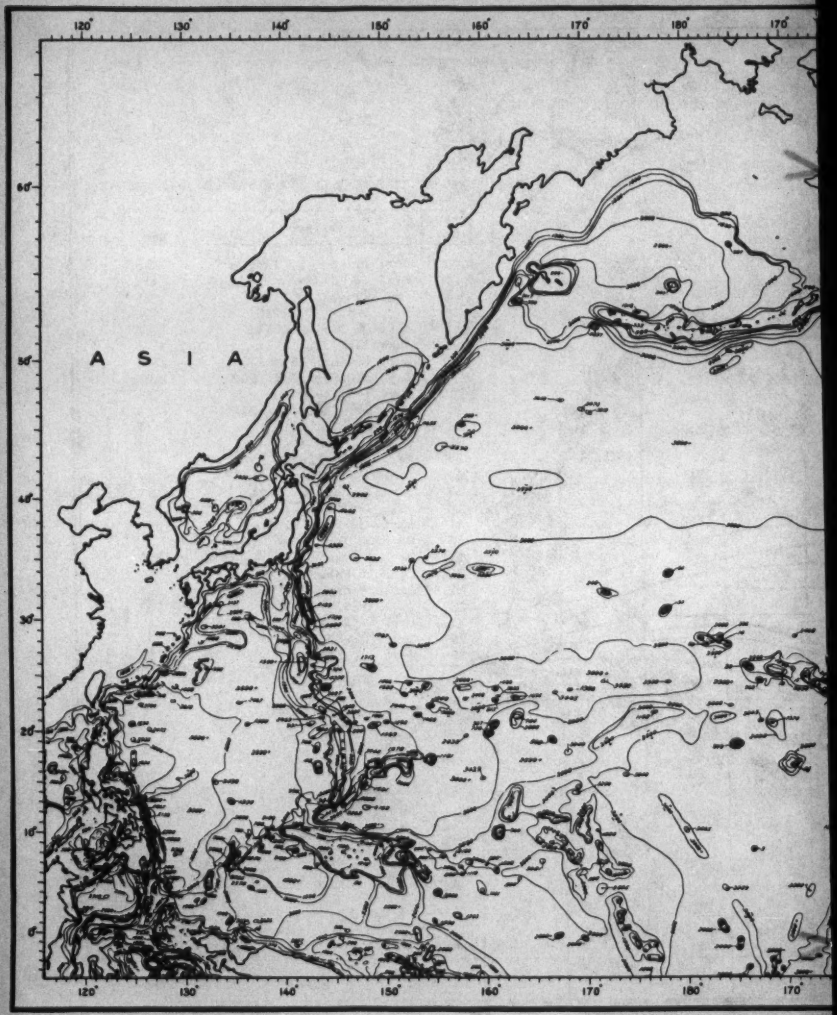
Fig. No. 3
NORTH PACIFIC OCEAN
INDEX CHART OF UNSOUNDED AREAS
Hatched portions show ocean-areas for which oceanic depths or deep-sea soundings have been observed and recorded on U. S. Hydrographic Office charts.
U.S.S. RAMAPO, between October 31, 1929, and January 5, 1933, crossed the North Pacific Ocean 25 times, taking sonic soundings on 23 passages mostly in unsounded areas, and using type S.E. 1987 (N. Electric Co.) machine, calibrated to velocity 1463 meters per second or 4800 feet per second. These passages with exception of Nos. 6 (only 21 soundings), 14, and 18 are shown by heavy black lines, figures in circles giving number of passages in chronological order and arrows giving direction of passages.

U.S.S. Nokomis - 200 sonic soundings taken off San Salvador (Watling Island) in 24° 05' N and 74° 20' 30" W.



TABULAR STATEMENT OF U.S.S. RAMAPO'S PASSAGES

Pass. No.	Time	No. of sdgs.
1	Oct. 31-Dec. 1, 1929	1275
2	Dec. 13, 1929-Jan. 6, 1930	110
3	Jan. 21-Feb. 21, 1930	1438
4	Mar. 5-Apr. 1, 1930	592
5	Apr. 28-May 4, 1930	1143
6	June 11, 1930	21
7	July 28-Aug. 25, 1930	1315
8	Sept. 20-Oct. 14, 1930	1163
9	Nov. 1-5, 1930	154
10	Dec. 14, 1930-Jan. 20, 1931	1346
11	Feb. 14-23, 1931	414
12	Feb. 26-Mar. 7, 1931	374
13	Mar. 19-27, 1931	323
14	No soundings	
15	June 16-July 7, 1931	1114
16	July 19-Aug. 20, 1931	596
17	Sept. 12-Oct. 5, 1931	972
18	No soundings	
19	Dec. 10, 1931-Jan. 5, 1932	700
20	Jan. 25-Feb. 16, 1932	575
21	Apr. 30-May 10, 1932	207
22	June 1-19, 1932	400
23	Aug. 9-19, 1932	235
24	Sept. 12-27, 1932	324
25	Dec. 16, 1932-Jan. 5, 1933	353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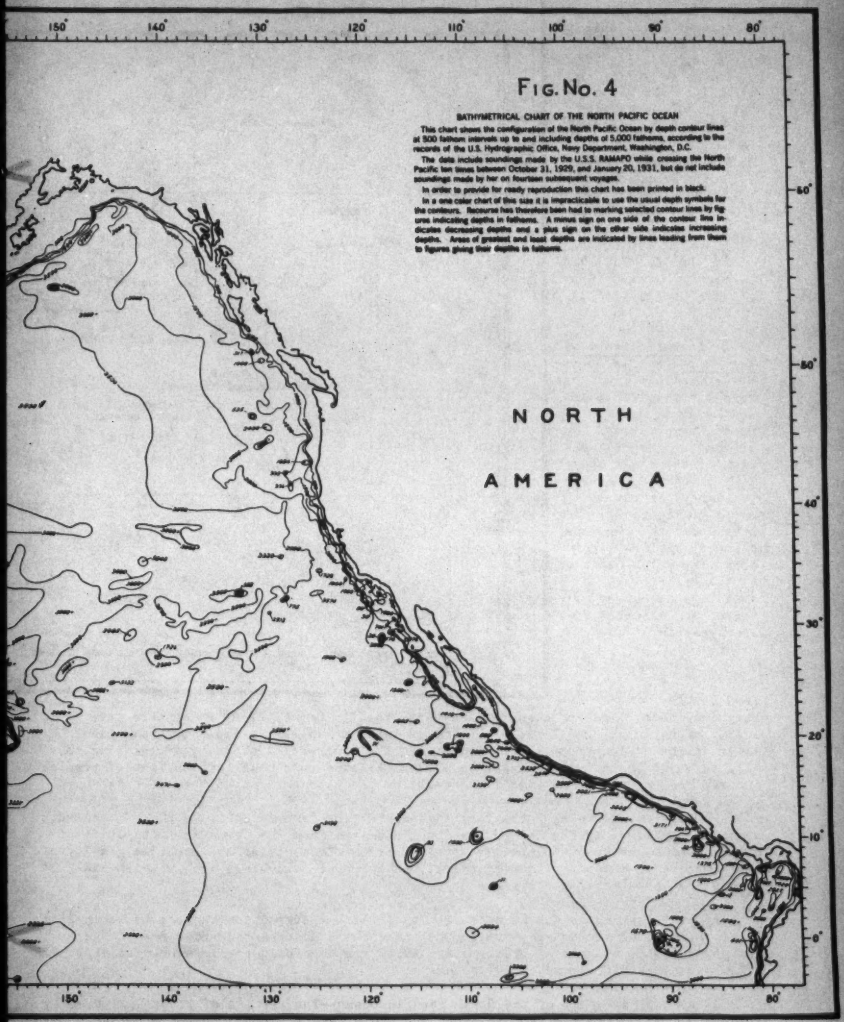


FIG. No. 4

BATHYMETRICAL CHART OF THE NORTH PACIFIC OCEAN

This chart shows the configuration of the North Pacific Ocean by depth contour lines at 500 fathom intervals up to and including depths of 5,000 fathoms, according to the records of the U.S. Hydrographic Office, Navy Department, Washington, D.C.

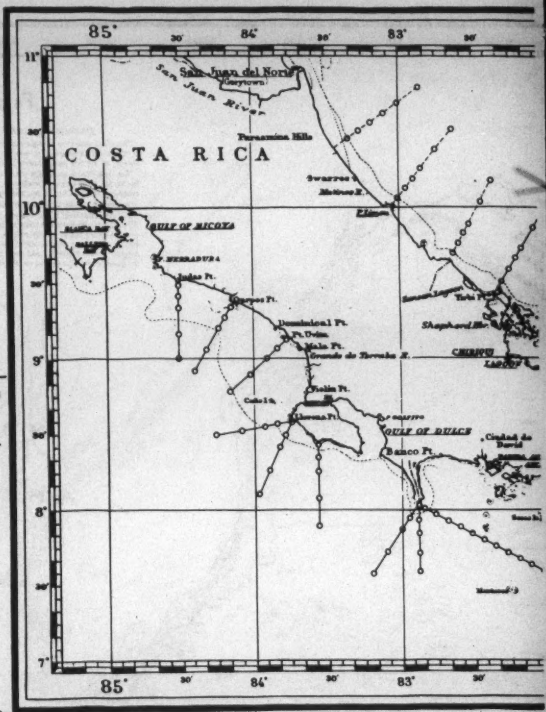
The data include soundings made by the U.S.S. RAMAPO while crossing the North Pacific ten times between October 31, 1929, and January 20, 1931, but do not include soundings made by her on fourteen subsequent voyages.

In order to provide for ready reproduction this chart has been printed in black.

In a one color chart of this size it is impracticable to use the usual depth symbols for the contours. Recourse has therefore been had to marking selected contour lines by figures indicating depths in fathoms. A minus sign on one side of the contour line indicates decreasing depths and a plus sign on the other side indicates increasing depths. Areas of greatest and least depths are indicated by lines leading from them to figures giving their depths in fathoms.

U.S.S. Hannibal - 45 sonic soundings obtained enroute Guantanamo Bay, Cuba, to Coco Solo, Canal Zone, crossing 17° 44' N in 75° 58' W, 16° 11' 45" N in 76° 37' 30" W, and 12° 03' 00" N in 79° 03' 00" W.

U.S.S. Nokomis - 450 sonic soundings taken enroute San Salvador to Port Sama, Cuba, crossing 24° 03' 45" N in 74° 21' 00" W, 15° 56' 30" N in 76° 26' 55" W, and 10° 18' 00" N in 79° 21' 25" W.



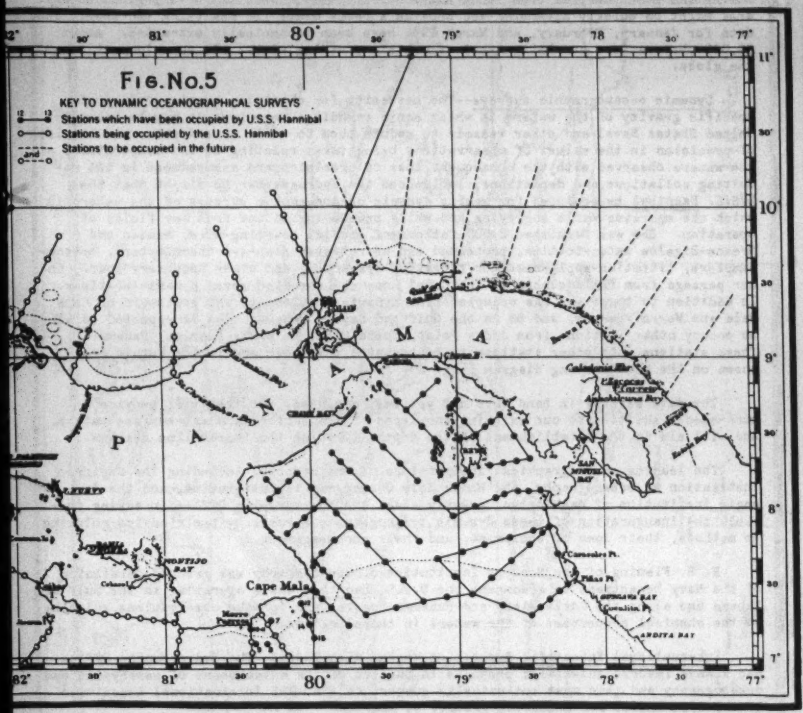
Unsounded areas of the North Pacific Ocean--While numerous soundings have already been taken in the North Pacific Ocean, many more are required for the delineation of the configuration of that Ocean with certainty, as may be noted on Figure 3. On this chart the portions colored gray are ocean-areas for which oceanic depths or deep-sea soundings have been observed and recorded on Hydrographic Office charts.

The U.S.S. Ramapo from October 1929 to January 1932 made 25 passages across the North Pacific Ocean, 16 of which were made in 1932, taking in all 15,114 sonic soundings. Her passages are shown by heavy black lines, numbered in chronological order, and their direction shown by arrows (Fig. 3). Only a few of the soundings taken have been utilized on account of the lack of precise information regarding the specific gravity of the waters in which they were taken.

Mention may be made of the fact that correction-factors for some 900 of the sonic soundings obtained by the Ramapo have been received from the Carnegie Institution of Washington, based upon the results obtained by the Carnegie of the specific gravity of those waters in which she took dynamical oceanographic soundings and in which the Ramapo also took sonic soundings.

As an illustration of the necessity of obtaining correction-factors to be applied to sonic soundings to obtain true depths, one of the uncorrected soundings of the Ramapo indicated a depth of 8,303 meters while the corrections gave a precise depth of 8,710 meters--a difference of 407 meters.

Bathymetrical chart of the North Pacific Ocean--The results of soundings taken by vessels of the United States Government and those received from various other authentic sources and recorded by the Hydrographic Office on its charts have been embodied in a bathymetrical chart of the North Pacific Ocean (Fig. 4), a copy of which is being pre-



pared for publication in the usual manner, that is, by variation in blue color for each 500-fathom gradient.

Current-charts--On the reverse sides of the Pilot Charts of the North Pacific Ocean for March, June, and September 1932, and January 1933, respectively, current-charts covering the greater portion of the North Pacific Ocean for the four seasonal quarters were presented. These current-presentations, previously published in two sections for each quarter, as now simplified enable the mariner to have more readily at his disposal data regarding averaged current-expectancies. The traverse resultant-drifts in the one-degree quadrangles are being worked up and it is expected that they will appear shortly. These drifts will assist the mariner in making more expeditious voyages.

Oceanic temperatures--The summarization of the observations by mariners of the temperatures of the surface-waters of the North Pacific Ocean observed during the years 1904-24, inclusive, has been completed and will be published shortly in the form of monthly charts showing the number of observations and the average temperature for each month in each one-degree quadrangle.

Mechanical extraction of oceanographic data--The mechanical extraction of data relating to currents, temperatures, sea and swell, and concomitant phenomena was begun

during the past year, in order that all such information relating to any given oceanic area might be quickly assembled and provide a ready means for analyzing the same. The data for January, February, and March 1932 have been mechanically extracted. About 20,000 observations are being received monthly covering almost all oceanic portions of the globe.

Dynamic oceanographic surveys--The necessity for obtaining precise values of specific gravity of the waters in which sonic soundings have been or may be taken by United States Naval and other vessels to reduce them to their true depths, and the lack of precision in the values of observations being taken relating to the temperatures of the waters observed with the consequent loss of precision and assuredness in the resulting collations and depictions, influenced the Hydrographer to direct that the U.S.S. Hannibal be equipped for making dynamic oceanographic surveys of the waters in which she operates while surveying and while proceeding to and from her fields of operation. She was furnished 2,000 fathoms of special sounding-wire, Nansen and Greene-Bigelow water-bottles, protected and unprotected deep-sea thermometers, bottom-samplers, titration-appliances for titrating sea-water, and other necessary gear. On her passage from Philadelphia to the Canal Zone she occupied seven dynamic stations. In addition to these she has occupied nine dynamic stations to the southward of Cape Mala and Morro Puercos, and 86 in the Gulf and Bay of Panama. She is expected to also occupy other stations from Judas Point, Costa Rica, to Morro Puercos, Panama. These stations with other stations to be occupied this year and in the future are shown on the accompanying diagram (Fig. 5).

The data already in hand have not yet been analyzed, but they will provide a much-needed addition to our existing knowledge of the surface and sub-surface waters, and will aid in the establishment of the depths to which the thermocline reaches.

The leading oceanographical institutions of the country, including the Scripps Institution of Oceanography, the Woods Hole Oceanographic Institution, and the Carnegie Institution of Washington, greatly aided the Hydrographic Office in making possible the inauguration of these dynamic oceanographic surveys by their advice relating to methods, their loan of equipment, and their encouragement.

R. H. Fleming of the Scripps Institution of Oceanography was granted permission of the Navy Department to accompany the U.S.S. Hannibal while operating in the Gulf of Panama and along the Costa Rican and Panaman coasts, and to make observations relating to the chemical properties of the waters in those regions.

International Scientific Expedition to the West Indies--The Hydrographic Office has always favored scientific projects in support of the advancement of geophysics and oceanography and gave most enthusiastic support to the 1932 International Expedition to the West Indies for measuring gravity at sea.

In this Expedition the Navy cooperated with Princeton University. The results of this work and that of the 1928 expedition, in which the Navy cooperated with the Carnegie Institution of Washington, have added 103 new gravity sea-stations in this disturbed area. A chart has been printed by the Hydrographic Office showing all of the final values of these latest gravity anomalies.

F. A. Vening Meinesz was in direct charge of all observations of both expeditions bringing with him his unique multiple-pendulum apparatus which when mounted on a submerged submarine is the only means which has been found adaptable for procuring precise oceanic-station values.

The course of the U.S.S. S-48, the submarine employed on the 1932 International Expedition, with positions of its gravity sea-stations is shown on the accompanying diagram (Fig. 6).

The final values for the 1932 expedition determined by the Hydrographic Office are given in the accompanying Table.

Navigators' Sailing Directions or Pilots--During the year 1932 the Hydrographic Office placed on issue five revised volumes of Sailing Directions and published recapitulatory supplements to the other volumes of the series. These books are designed

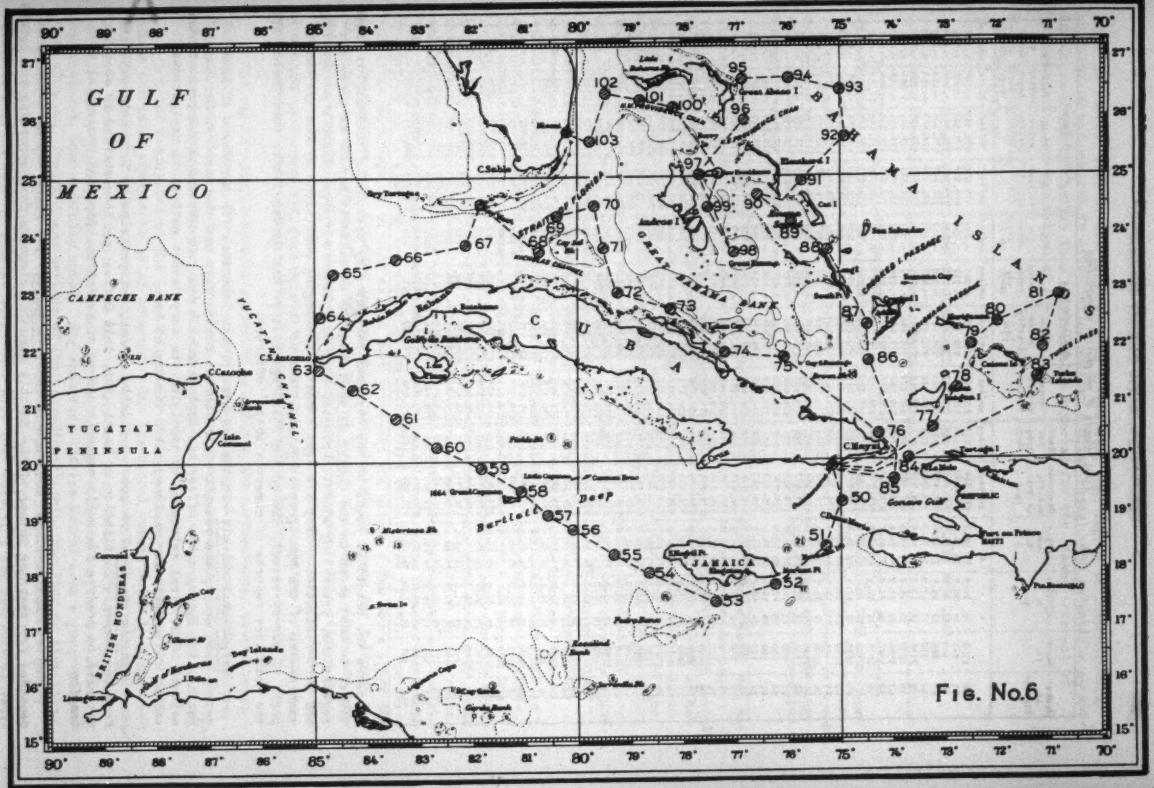

GULF
OF
MEXICO
CAMPECHE BANK
YUCATAN
PENINSULA
YUCATAN CHANNEL
CUBA
GREAT BAHAMA BANK
BAHAMA ISLANDS
JAMAICA
Bartlett Deep
BRITISH HONDURAS
90° 89° 88° 87° 86° 85° 84° 83° 82° 81° 80° 79° 78° 77° 76° 75° 74° 73° 72° 71° 70°
27° 26° 25° 24° 23° 22° 21° 20° 19° 18° 17° 16° 15°

Fig. No.6

FINAL RESULTS OF THE GRAVITY MEASUREMENTS

Number of Station	Depth fm.	Latitude N. φ	Longitude W. λ	Observed Gravity at Sta. (g_o)	Corr. for Topog. Comp.	Bowie Formula				Helmert Formula			
						Theoretical Gravity (γ)	Computed Gravity (g_c)	Isostatic Anomaly ($g_o - g_c$)	Free Air Anomaly ($g_o - \gamma$)	Theoretical Gravity (γ)	Computed Gravity (g_c)	Isostatic Anomaly ($g_o - g_c$)	Free Air Anomaly ($g_o - \gamma$)
		° ′	° ′	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²	cm/sec²
50	1590	19 14.5	74 58.0	978.560	−.057	978.598	978.561	−.001	−.038	978.590	978.595	+.007	−.050
51	920	18 26.0	75 16.0	978.582	+.016	978.554	978.570	+.012	+.028	978.566	978.582	+.020	+.036
52	540	17 44.0	76 14.0	978.551	+.034	978.517	978.551	−.000	+.034	978.509	978.545	+.008	+.042
53	860	17 25.0	77 22.0	978.485	−.007	978.500	978.495	−.010	−.017	978.492	978.485	−.002	−.009
54	770	17 57.0	78 39.5	978.522	+.025	978.528	978.551	−.029	−.006	978.520	978.545	−.021	+.002
55	2130	18 19.0	79 18.0	978.536	−.053	978.598	978.451	+.085	−.062	978.550	978.585	+.053	−.014
56	2630	18 46.0	80 06.0	978.565	−.083	978.572	978.489	+.076	−.007	978.564	978.481	+.084	+.001
57	3590	19 02.5	80 34.0	978.499	−.158	978.587	978.429	+.070	−.088	978.579	978.421	+.078	−.080
58	1380	19 07.0	81 06.0	978.614	+.016	978.610	978.626	−.012	+.004	978.609	978.618	−.004	+.012
59	1810	19 35.5	81 49.5	978.595	−.020	978.634	978.616	−.021	−.039	978.628	978.608	−.013	−.033
60	2510	20 18.0	82 38.0	978.658	−.076	978.659	978.585	+.073	−.001	978.651	978.575	+.083	+.007
61	2630	20 47.5	83 24.5	978.679	−.087	978.688	978.601	+.078	−.009	978.680	978.595	+.086	−.001
62	2140	21 18.0	84 16.0	978.717	−.066	978.719	978.653	+.064	−.002	978.711	978.645	+.072	+.006
63	1400	21 40.0	84 55.0	978.709	−.025	978.743	978.702	−.017	−.042	978.734	978.711	−.009	−.033
64	1280	22 35.0	84 54.5	978.756	−.055	978.799	978.766	−.010	−.043	978.792	978.759	−.003	−.036
65	1390	22 21.5	84 36.0	978.852	−.054	978.850	978.816	+.019	−.015	978.842	978.806	+.027	−.007
66	1150	23 56.0	83 24.0	978.826	−.050	978.868	978.836	−.010	−.048	978.858	978.826	−.002	−.032
67	930	23 07.0	82 07.0	978.855	−.054	978.881	978.837	+.017	−.046	978.871	978.833	+.021	−.038
68	690	23 43.0	80 45.5	978.851	−.020	978.872	978.852	−.021	−.041	978.864	978.844	−.013	−.033
69	560	24 18.0	80 24.5	978.879	−.017	978.912	978.895	−.016	−.033	978.905	978.888	−.009	−.026
70	470	24 50.0	79 41.5	978.885	−.008	978.926	978.918	−.025	−.041	978.918	978.910	−.027	−.033
71	280	25 17.0	80 08.0	978.878	+.010	978.935	978.882	−.014	−.057	978.926	978.882	−.006	−.047
72	230	27 58.5	79 14.5	978.815	+.016	978.874	978.838	−.029	−.011	978.816	978.850	−.017	+.005
73	300	27 59.5	78 15.0	978.798	+.002	978.804	978.806	−.008	−.006	978.796	978.798	−.000	+.002
74	1200	27 56.0	77 12.5	978.674	−.069	978.758	978.689	−.015	−.084	978.750	978.681	−.007	−.076
75	1490	27 49.5	76 03.5	978.641	−.069	978.752	978.687	−.047	−.111	978.744	978.675	−.034	−.103
76	1060	28 28.0	74 17.0	978.595	−.015	978.670	978.647	−.052	−.075	978.663	978.641	−.046	−.067
77	1860	29 32.5	73 15.0	978.486	−.074	978.674	978.600	−.114	−.188	978.666	978.592	−.106	−.180
78	2130	21 15.5	72 44.5	978.572	−.068	978.716	978.648	−.076	−.144	978.708	978.640	−.068	−.136
79	2080	29 02.5	72 50.0	978.696	−.057	978.765	978.728	−.032	−.069	978.757	978.720	−.024	−.061
80	2810	27 37.5	71 58.0	978.747	−.054	978.802	978.748	−.006	−.060	978.791	978.740	+.002	−.052
81	2960	22 51.0	70 44.0	978.789	−.055	978.816	978.781	+.008	−.027	978.808	978.773	+.016	−.019
82	2170	21 57.0	71 08.0	978.719	−.017	978.759	978.742	−.030	−.047	978.751	978.734	−.029	−.039
83	1040	21 25.5	71 14.5	978.755	+.047	978.726	978.775	−.020	+.027	978.718	978.766	−.012	+.035
84	1780	20 39.5	70 47.5	978.479	−.066	978.644	978.578	−.099	−.165	978.635	978.564	−.085	−.156
85	1660	19 58.0	74 00.0	978.573	−.055	978.621	978.568	+.005	−.048	978.615	978.560	+.013	−.040
86	1550	21 46.0	74 26.0	978.705	−.028	978.748	978.720	−.015	−.043	978.740	978.719	−.007	−.035
87	1270	22 22.0	74 50.0	978.765	+.005	978.785	978.788	−.029	−.020	978.777	978.780	−.017	−.014
88	1120	23 14.0	75 14.0	978.865	+.009	978.874	978.930	−.015	−.007	978.857	978.920	−.007	−.001
89	1050	24 12.0	75 54.5	978.842	−.001	978.906	978.904	−.062	−.063	978.897	978.896	−.054	−.055
90	860	24 39.5	76 34.0	978.897	−.002	978.956	978.934	−.037	−.059	978.928	978.926	−.029	−.031
91	2670	24 56.0	75 12.5	978.847	−.090	978.955	978.845	+.018	−.108	978.948	978.858	−.011	−.101
92	2950	25 40.0	74 59.0	978.905	−.027	979.006	978.979	−.074	−.101	978.999	978.979	−.053	−.074
93	2540	26 27.0	75 00.0	979.059	−.022	979.062	979.040	+.019	−.003	979.054	979.052	+.027	+.005
94	2670	26 40.0	75 58.5	979.055	−.055	979.077	979.022	+.011	−.044	979.070	979.015	+.018	−.037
95	1130	26 39.5	76 49.0	979.082	+.022	979.074	979.098	−.015	+.007	979.069	979.091	−.008	+.014
96	2440	25 58.0	76 49.0	978.876	−.098	979.078	978.930	−.054	−.152	979.070	978.922	−.047	−.144
97	1780	25 01.7	77 40.7	978.868	−.055	978.962	978.907	−.039	−.094	978.954	978.899	−.031	−.086
98	740	25 41.0	76 59.5	978.791	−.021	978.871	978.850	−.059	−.080	978.865	978.842	−.051	−.072
99	890	24 57.5	77 50.0	978.859	−.056	978.923	978.887	−.028	−.084	978.915	978.879	−.020	−.076
100	580	24 10.5	78 11.0	979.029	−.002	979.045	979.041	−.012	−.014	979.035	979.033	−.004	−.006
101	500	23 18.5	78 49.0	979.026	+.014	979.052	979.066	−.040	−.026	979.044	979.058	−.032	−.018
102	350	26 25.0	79 25.0	979.044	+.004	979.060	979.064	−.020	−.016	979.052	979.056	−.012	−.008
103	350	25 35.0	79 48.5	978.986	.000	979.000	979.000	−.014	−.014	978.993	978.993	−.007	−.007

to serve the practical needs of the overseas navigator by presenting information additional to that shown on the charts on such subjects as national marine services and regulations, prevailing winds, currents, fog, ice, oceanic routes, inshore navigation, and port-facilities. They are kept abreast of changing conditions by the systematic examination of the hydrographic publications of foreign maritime countries, the reports of survey-vessels and of the field agencies of the United States Government, and the voluntary reports of numerous ships' officers.

Navigational manuals--In the exercise of its functions for the means of navigating with safety the vessels of the United States Navy and the American Merchant Marine, the Hydrographic Office has kept pace with the progress and development of the science of nautical astronomy by supplying the very latest methods in navigational tables and manuals for rapid position-finding at sea.

Magnetic charts--From every available source, but principally from data supplied from the Carnegie Institution of Washington, this Office has been enabled to analyze material to produce its world magnetic charts of variation, dip, and horizontal intensity.

The destruction of the non-magnetic ship Carnegie, upon which the maritime world depended for securing values of the Earth's magnetic elements for correcting the latest

magnetic charts, will necessitate, as time progresses, some degree of international cooperation and support in establishing another similar vessel with scientific personnel to continue to furnish this indispensable material for the common interest of transportation and navigation of the sea.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC WORK OF THE COAST GUARD IN 1932 AND PLANS FOR 1933

R. M. Boyle

In 1932 three vessels were assigned to Ice Patrol duty. Two of these vessels were first-class cutters of approximately 250 feet in length and 2,000 tons displacement. These two vessels alternated on patrol in the vicinity of the Grand Banks during the months of April, May, and June. Their duties were to locate and keep in touch day by day with icebergs and pack-ice, determine their set and drift, report the location of the ice to the Hydrographic Office of the Navy, and broadcast the information by radio for the protection of shipping.

The third vessel, a 125-foot patrol-boat equipped for oceanographic work, was assigned the duty of making a preliminary observation-cruise to determine ice-conditions prior to the inauguration of the regular patrol, and after the continuous patrol was begun this vessel was used exclusively for oceanographic work. The object of her work was to make during the ice-season regular oceanographic surveys about the Grand Banks of the critical ice-regions. Based upon these observations, the charts of the dynamic circulation were to be constructed for the immediate use of the larger ice-patrol vessels. This vessel carried Olav Mosby of the Geophysical Institute of Bergen, Norway, to carry out the oceanographic program. The special oceanographic equipment of the General Greene consisted of 12 Nansen water-bottles, Richter and Wiese deep-sea reversing-thermometers, titrating-outfit, and an electrical conductivity-salinometer, together with the necessary winches for hoisting the bottles. Serial temperatures and salinities were observed in deep water down to 2,000 meters and in shallow water to close to the bottom. On each water-bottle two reversing-thermometers were used. The thermometers were always allowed three minutes or more at the depths of observation before they were reversed. The thermometers were read to 0°.01 with the aid of a magnifying-glass. The depths of observations were checked by means of unprotected thermometers. The chlorinities were determined on board by titration, and salinities and densities were determined from tables based on Knudsen's formula. Then the dynamic circulation was computed and current-charts drawn in accordance with the method of V. Bjerknes and described in Coast Guard Bulletin 14 (1926). The calculations were kept up to date as the work proceeded and within a few hours after the last observations were taken the current-charts were invariably ready for delivery to the patrol vessel. It was found that the General Greene could make a survey and produce a current-chart of the critical area once each three weeks. This allowed her time to proceed to St. Johns, Newfoundland, for fuel and supplies between each survey During the season three complete surveys were made and current-charts furnished the patrol-vessel. Each survey consisted of about 35 to 40 stations.

The regular patrol-vessels collected by radio 6,028 surface-water temperatures during the ice-season from vessels crossing the vicinity of the Grand Banks. These, together with the water-temperatures observed on the patrol-vessels, were used to construct isotherm charts for each 15-day period.

A brief discussion of the practical use of the dynamic current-charts and isotherm charts is thought to be of interest. The ice-patrol vessel tries to keep track from day to day of the southernmost ice, particularly when it is in or near the transatlantic lane routes. This is done by visiting each berg daily that threatens the steamer lanes. Its position, set, and drift, together with the surface sea-water temperatures, are carefully noted. Fog enshrouds the ice-patrol area a great percentage of time. During these periods of fog, sometimes lasting for four or five days, or even for longer times, no scouting for ice can be done, and the known bergs are lost. It is readily seen that being able to accurately predict the drift of the ice would be a great help in finding bergs that have been lost in a fog for several days.

Also a current-chart of the ice-regions would indicate areas that are most likely to be berg-infested.

Both the dynamic current-charts and the surface-isotherm charts were used in 1932 in predicting ice-drifts. The surface isotherms are assumed to give a general idea of the prevailing water- and ice-movements. The ice is expected to be found and to remain where the water is coldest. A great percentage of the observed drifts of bergs have been found to follow rather closely the direction of the surface isotherms. During the ice-season of 1932 the isotherm charts agree with dynamic charts drawn for the same period to a great extent. Five bergs drifted south of the tail of the Grand Banks during the past ice-season and were closely watched until they disappeared. The drifts of four of these bergs agreed fairly closely with the drifts computed dynamically, and also with the surface-isotherm charts. The fifth berg drifted in accordance with the current-charts until it reached a point west of the tail of the Banks on May 21. Where both isotherm and dynamic current-charts indicated that the currents were southerly, curving to the southeast, this berg drifted north until May 24, when it remained practically stationary until it was lost in a fog on May 26 and not sighted again. Another berg that was just one day's drift behind this berg drifted exactly as it was expected.

With all the available means of predicting the drifts of icebergs, past knowledge of ice-drifts, isotherm charts, and dynamic current-charts, it is believed that, while this information is invaluable to the ice-patrol vessel in locating ice lost during a fog or bad weather and in deciding the areas to be scouted for approaching ice, the information is not accurate enough to be used in broadcasting to shipping the probable positions of bergs not sighted recently due to fog or other reasons. If an infallible current-chart could be constructed frequently enough to predict the positions of bergs not sighted for a week or longer, fog and the ice-menace would be beaten.

During the current year no changes are contemplated in the method of conducting the ice-patrol. The General Greene will make frequent oceanographic surveys in the vicinity of the Grand Banks and much the same program as last year will be carried on. Floyd M. Soule is the oceanographer on the General Greene this year. The surface-isotherm charts will also be constructed as in former years.

After the discontinuance of the ice-patrol the General Greene will make a cruise of about one month's duration in Davis Strait. She will occupy approximately 125 oceanographic stations, making much the same cruise as she did in 1931. Ice-conditions in this region will also be noted. Echo-sounding with the fathometer will be made at frequent intervals.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC WORK OF THE COAST AND GEODETIC SURVEY DURING THE PAST YEAR

R. R. Lukens

The high light in the oceanographic accomplishments of the Coast and Geodetic Survey for the past year was the completion of the survey of Georges Bank. Three field-seasons were spent on this work and, during the past two summers, four vessels of the Survey were at work on the project. All records of the Survey in hydrographic work were broken last summer. In one stretch of about 50 hours, the Oceanographer ran over 700 miles on a continuous sounding-line, all of which was controlled radio-acoustically from station-ships at anchor on the banks. The Oceanographer is the former yacht Corsair, which was presented to the Coast and Geodetic Survey by J. P. Morgan in 1930. She is a splendid ship with a speed of 15 knots and has proven a valuable unit in the survey of the offshore waters of the Atlantic Coast.

In the survey of Georges Bank, a new feature was introduced into oceanographic work, that of rigid control. In deep-sea work where the bottom is usually flat, no great attention is usually applied to the matter of obtaining the geographic positions of the soundings. The customary navigation-sights are taken and the run is adjusted

to fit these various fixes. On an offshore chart, the space taken up by the figures denoting the soundings is so great that extreme accuracy in locating the sounding is not necessary.

In the case of such an area as Georges Bank, however, it is of utmost necessity that the sounding-lines be controlled as rigidly as possible, for without such control it would never be possible to get sounding-lines to cross and uncertainty would be sure to creep into the finished product.

The development of radio acoustic sound-ranging by the Coast and Geodetic Survey made a rigid control possible for such an area where the surveying must be done far out of sight of land.

Briefly, the radio-acoustic, sound-ranging system consists of measuring distances through the water by determining the time it takes sound to travel through the water. The system is highly technical, but is so devised that the chronograph is located on the sounding-vessel and the officers can compute the distances as soon as the chronograph registers the signals from the two or more hydrophone-stations. Thus within three or four minutes after the bomb is exploded it is possible to lay down the position on the survey-sheet. By obtaining frequent positions, the ship can be guided to run any system of lines which has been determined upon.

In some instances on Georges Bank, the two ships doing the sounding were operated in tandem. The lead ship did the bombing and furnished the control and the other ship kept the required distance off by means of a range-finder. At certain intervals, bearings were taken on the lead ship. When the positions of the lead ship were plotted on the sheet, it was a simple matter to plot the track of the second ship. This system was found desirable only when running long lines over uniform bottom and in clear weather when the ships were intervisible. With single-ship hydrography, the radio-acoustic method makes it possible to sound at night or in fog, and the only difficulty is the ordinary hazard of thick-weather navigation.

For the control of Georges Bank, a system of buoy-triangulation was carried over the bank and extended to a connection with the shore-triangulation of Cape Cod.

In the beginning of the survey, the Lighthouse Service planted three permanent buoys which were to remain in place through each winter until the survey was finished. This was necessary in order that the work of one summer might be correlated with the work of the next season.

These buoys were located astronomically by a large number of sextant-observations made from a ship anchored near the buoy. In the case of each sight, the distance and bearing of the buoy were determined and the sight related to the buoy. Great care was taken with these sights. Only the finest sextants were used and every possible refinement was made. Care was taken to take sights only when it was thought that there was no uncertainty concerning the horizon, and observations were taken only during the most favorable periods of morning and evening twilights.

The lines of position of these observations were plotted and, after careful study, the most probable point was selected. At the time it was felt that the selected position of the buoy was probably correct to about 200 yards.

Numerous survey-buoys were planted over the banks and these buoys were "bombed in," as the field-officers call it. A station-ship would be anchored close to one buoy and the surveying-ship would explode a bomb at the other buoy. This would be repeated several times and the mean result accepted after correcting for various eccentricities. The buoys were generally planted in the form of quadrilaterals and all sides and the diagonals bombed.

The true azimuth between buoys was determined by sextant-angles from the Sun or other body near the horizon. In accomplishing this, the ship maneuvers to get the two buoys in line and then a sextant-observer measures the inclined angle between the celestial body and the buoys.

The position of one of the permanent buoys was held fixed and the various buoys

were plotted according to the radio-acoustic distances and the true bearings. This system of buoy-triangulation was carried for a distance of some 150 miles to the navigational buoys off Cape Cod, and the error of closure was only about 400 yards, which was considered a most remarkable agreement.

This result indicated that the astronomic position of the permanent buoy was very nearly correct and that the velocities used in the computations were also very near the true values.

A chart of Georges Bank designed specially for the use of the fishing-fleet has been issued. This chart contains many features of special use to the fishermen. It is the first accurate and complete chart ever published of this great area, which has been the most feared locality of the North Atlantic Ocean since the colonial days. While Georges Bank is usually considered a danger of the front rank, it has at times proven a haven. During the Revolution, several heavily armed French vessels fell in with a small British sloop of war. They immediately gave chase and it looked as though they would soon overtake and destroy the little sloop. The Britisher had different ideas, however, and, with a fair wind, headed his vessel direct for Georges Shoals. Being of lighter draft, he sailed in among the shoals, while the heavier French vessels gave up the chase and headed for safe water. That British ship was commanded by a resourceful young officer who afterwards became Lord Nelson.

One of the important by-products of the Georges Bank survey was the current-observations made from the station-ships while at anchor at various stations scattered over the banks. In all, 130 days of current-observations were obtained. In addition, a great many observations were made for temperature and density. The matter of water-temperatures is very important for such a survey, as an adequate knowledge of water-temperatures, especially bottom-temperatures, is necessary in determining the correct velocity of sound through sea-water. As there is a considerable monthly change in the water-temperatures, the observations had to be continued throughout the field-season.

On her trip from Norfolk to the winter working-grounds in the Gulf of Mexico, the Oceanographer ran a line of deep-sea soundings from Cape Hatteras to the Bahamas, and from Tortugas to Sabine Bank. On her return trip in April 1933, the same ship will run a similar and parallel line. This ship is equipped with one of the new recording-fathometers recently developed by the Submarine Signal Corporation. The graphs obtained show in a very vivid manner the profile of the bottom and afford permanent records.

On the Pacific Coast, two vessels have continued offshore surveys along the California coast, carrying the hydrography out to the 2,000-fathom curve in most places. This work is also controlled by radio-acoustic sound-ranging, but the method differs slightly from that used on the Atlantic Coast. Due to the deep water and bold shores on the Pacific, station-ships are not used, but instead magnetophones are planted usually in depths of seven to ten fathoms and connected to a shore radio-station by cable.

Both radio-acoustic range-finding and echo-sounding have been carried on with greater success on the Pacific than on the Atlantic. A greater range has been attained on the Pacific, the record being something over 200 miles. At this distance the bombs were still being heard, but the radio failed. With the echo-sounding apparatus the ships on the Pacific have consistently been able to get greater depths with more certainty than on the Atlantic. The reasons for this have not yet been fully determined.

The Pioneer working off Southern California recently discovered a ridge with 300 fathoms over it well outside the continental shelf. This bank lies 90 miles south of Point Conception. When the discovery of this bank became known, fishermen immediately became interested and wanted to know its exact location, which, of course, was furnished them. As the inshore fishing-grounds become depleted, the fishermen push farther and farther offshore and are much interested in locating new banks. The discovery of this bank brings up the speculation as to other similar banks lying off the offshore edge of the continental shelf. This question can be determined only by extensive oceanographic work.

In southwestern Alaska, the Surveyor and Discoverer have nearly completed the survey of Kodiak Island and the extensive banks surrounding it. On their trips from Seattle to Alaska they are running lines of echo-soundings which will add much to our knowledge of the hydrography of the North Pacific and the Gulf of Alaska. During the coming season the Discoverer will develop the bank lying 175 miles southeast of Kodiak Island. This bank was discovered by the Pioneer in 1925. A single line of soundings across it revealed a depth of 227 fathoms, surrounded by general depths of 2,000 fathoms and more. It is known that certain fishing-vessels have visited this bank and made large catches. It will be interesting to learn the least depth and extent of this bank--which so far has not been named.

In connection with the tide- and current-work of the Coast and Geodetic Survey, a total of 33 primary tide-stations was maintained throughout the year; of these, 20 are on the Atlantic and Gulf coasts, ten on the Pacific Coast, two in Alaska, and one in the Hawaiian Islands.

Work now in progress includes a tide-survey covering about 300 miles of the west coast of Florida northward of Cape Romano. Continuous automatic gage-records are to be secured for a period of one year at seven selected stations along the coast.

A similar survey is being executed along the Pacific Coast of the United States from Crescent City, California, to the vicinity of the Columbia River. A continuous record covering a period of one year will be obtained at each of 12 tide-stations, and, as in the Florida survey, a number of supplemental short-series stations will be established and precise tidal data will be derived by correlation with the results from the one-year series.

The results derived from these records will furnish information on the local characteristics of the tide at each station for the use of navigators, engineers, and others. They will provide precise determinations of the basic tidal datum-planes from which elevations of the land and depths of the sea are reckoned. The precise mean sea-level determinations made at the long-series stations will serve as tie-in points for the precise level-net which covers the entire country.

Last summer, through cooperative arrangement with the United States Engineers, a comprehensive tide- and current-survey was made of New York Harbor and environs. During this survey this Bureau secured tide observations at 17 stations and 174 day current-observations at 85 locations.

While engaged on control survey-work in South Carolina, the ship Lydonia also conducted, during the past winter, a current-survey of Charleston Harbor. Observations covering 42 days at 21 locations were made. Current-observations are made both by the simple current-pole and by the more complicated current-meters.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AIR- AND WATER-TEMPERATURES IN THE WEST INDIAN REGION

W. F. McDonald and A. K. Showalter

The physical conditions that prevail in the surface of the oceans are largely controlled by the overlying atmosphere. It influences the temperature, salinity, and motion of the sea-surface. The thermal relationship between the ocean and the air is of fundamental importance to all the phenomena of both masses.

The available data on the average temperature-conditions at sea are usually separated into independent charts or tables for air and water. There seems to be little available in the way of studies of the average temperatures of atmosphere and sea-surface considered as inseparable aspects of an energy-situation.

These considerations lead us to present some details from a computation of all the meteorological observations available in the files of the United States Weather Bureau, gathered from ships in the Antillean area, south of Bermuda, and eastward to

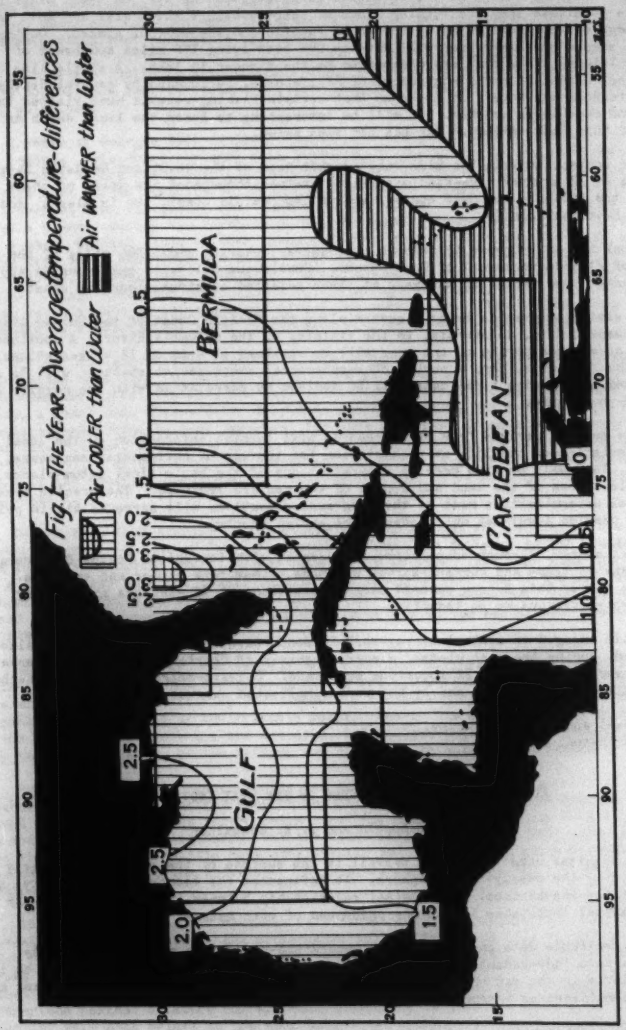


Fig. 1—The Year- Average temperature-differences
Air COOLER than Water
Air WARMER than Water
BERMUDA
GULF
CARIBBEAN

longitude 52°.5 during the years 1915 to 1929, inclusive. These computations were made from data tabulated for revision of the Central American Waters Pilot Chart of the United States Hydrographic Office.

The opening of the Panama Canal has brought into the region since 1914 such changes of shipping-routes and so increased the number of the ships as to give a very credible basis for average values in all parts of the region. Some areas have, of course, furnished very much larger numbers of observations than others. The general density of observations is least in the extreme eastern end of the region, and increases roughly westward into the Gulf and western Caribbean, with an extraordinary concentration of observations in the Florida Straits.

Into the sea- and air-temperature records herein discussed, about 400,000 individual temperature-readings have been transcribed and summarized. The work was prosecuted upon rectangular units of 2°.5 on a side, or one-fourth of the former unit of publication in 5° squares.

Details of the statistical methods applied, and of the critical considerations underlying some of the judgments herein expressed cannot, for the lack of space, be given, but the masses of data give to the average values presented, limits of probable error amounting to less than one-tenth of a degree in the case of general area or annual averages, and of the order of three-tenths of a degree or less in most of the individual monthly values.

The first step in the study of the relations between sea- and air-temperatures in the region covered was the computation of the 15-year averages of monthly temperatures by 2.5-degree squares. These values were then compared, and the differences computed. Where the water averaged warmer than the overlying air the difference was called "positive," because in that case the air gains energy by acquisition of both heat and moisture. The differences of opposite sign, that is, for air warmer than water, were thus termed "negative," as indicating lessened opportunity for the air to acquire any energy from the sea-surface.

Averages of these differences for the 12 months (shown as Fig. 1) reveal that for the year as a whole the positive type is dominant over about 80 per cent of the entire region. Air is prevailingly warmer than the underlying water-surface only in a small section roughly south of the latitude of Puerto Rico and east of longitude 75°.

The months from April to August show the major incidence of the negative type of difference, which is at its maximum extent and intensity in June (see Fig. 2). At that time it covers the eastern half of the region charted, but the greatest excess of air-temperature over water-temperature barely exceeds 1°.5, even at the extreme eastern end of the area.

Positive type-differences prevail during the entire year over nearly all of the region lying west of longitude 80°. In other words, the western half of the chart is dominated by air cooler than water at all seasons, and this type of situation extends east of 80° in the cooler months from September to March. In December and January, positive differences prevail over practically all of the region, and reach maximum values of 5° to 6° over the northern Gulf of Mexico and the Gulf Stream off northern Florida. The chart for December (shown as Fig. 3) reveals the area of positive differences at its greatest extent, covering more than 95 per cent of the entire region.

Cooler air therefore is shown to be persistent near the continent. It must be supposed that continental influences enter into this situation throughout the year, but the influence is considerably intensified during the winter season.

The case wherein air reaches average temperatures above those prevailing on the water-surface represents a marine rather than a continental type of influence, since this situation is confined to the more eastern parts of our charts.

The procession of changes in the areal distribution of positive and negative temperature-differences, from month to month, is remarkably regular and consistent. This smooth progression of changes is strong confirmation of the general accuracy of the underlying data. It seemingly admits no element of the accidental in the re-

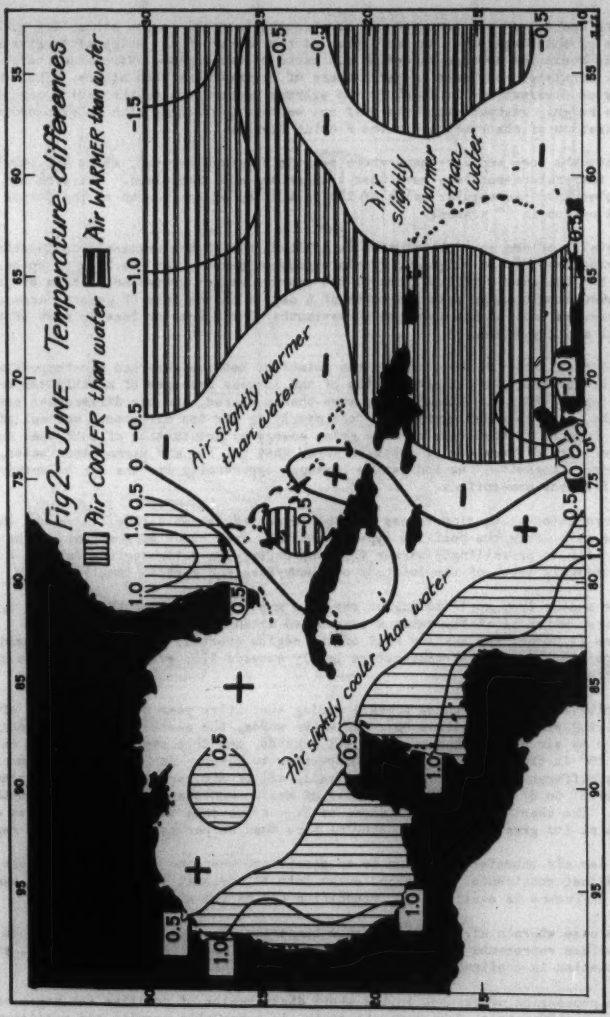


Fig 2-JUNE Temperature-differences
Air COOLER than water
Air WARMER than water
Air slightly warmer than water
Air slightly warmer than water
Air slightly cooler than water

Fig. 3-DECEMBER Temperature differences
Air more than 3°Cooler than water
Air ½° to 3°Cooler than water
Air slightly cooler than water
Air slightly warmer than water

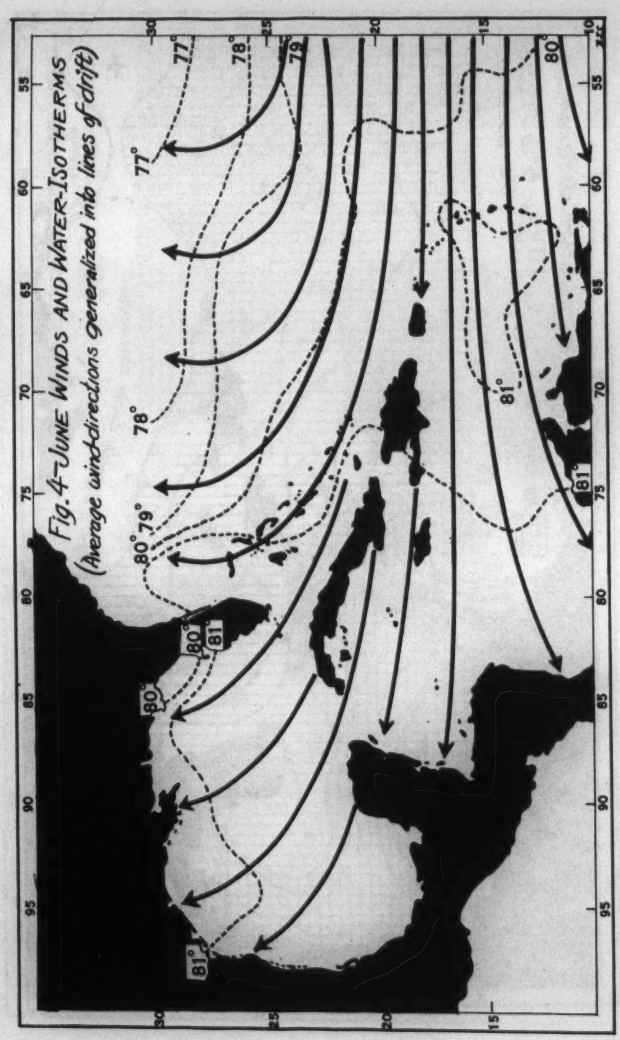


Fig. 4-June Winds and Water-Isotherms
(Average wind-directions generalized into lines of drift)
77°
78°
79°
80°
81°

sultant picture of a persistence of the positive condition near the Continent in summer, and of the increase in intensity and spread of the area dominated by cooler air as the season advances to the winter solstice.

The physical explanation of the winter-type of relation does not seem particularly difficult. Continental air at that season finds its way well out over the Atlantic, and also drifts far southward into the Caribbean. The generalized lines of average wind-direction are indicated for December on Figure 5, which is based upon the results of tabulations of wind-directions in each square, arrived at in the course of the compilation of the 15 years of observations on which all of this work is based.

In winter, air of continental origin is characterized by relatively low temperatures and also by low humidities. Such a mass will make a heavy demand upon the water-surface for heat and moisture when moved east or south over warm seas. Since the air-drift depicted by Figure 5 would carry continental air over progressively warmer surfaces, and the moisture deficit requires considerable time for satisfaction, the air remains cooler than the water through remarkable distances away from the continental borders.

The temperature-situation in June (Fig. 2) should be compared with the lines of average air-drift in that month (Fig. 4). The latter chart reveals that there is in the summer a general transport of air westward from ocean to continent, with outflow northward from the belt of trade-winds that extends into the West Indies.

As might be expected from this picture of an average surface-air transport of marine origin, there is in June but small difference between air- and water-temperatures. The persistence of positive temperature-differences of small order near the western shores indicates that the stream-lines must be interpreted with caution, and cannot be regarded as representing steady flow of air along the lines indicated. Rather, the wind-charts show that all the veriable directions of surface-winds, when resolved into average directions, admit of the generalized picture of resultant drift which is here presented. It must not be forgotten, however, that origin of air at any place and time is not ascertainable from such a chart, and that even in summer considerable continental-air finds its way well out over the Gulf of Mexico where it supports the small positive temperature-situation revealed in that area.

Similar logic fails, however, to supply a complete explanation for the summer areas of negative temperature-difference. In the Bermuda section there is in June an average transport of air from warmer to cooler water-surfaces which might explain the situation in that small quarter. But there is no similar evidence of transport from a warmer surface to support the negative temperature-situation over the southeast quarter of the chart, for, in part of that region, the water-surface is itself warmer than any adjacent marine or land area.

Another interesting phase of the study of temperature-relations in the West Indian region is the seasonal march and range of the average air- and water-temperatures in the several parts of the large area studied. To reduce this phase of the matter to terms affording proper comparisons, the major area was subdivided into three key-sections of 16 squares each, designated for the sake of brevity as the Caribbean, the Gulf, and the Bermuda sections. The boundaries of these subdivisions are shown by the heavy-bordered blocks in Figure 1.

Within each of these typical regions the average monthly air- and water-temperatures for the section as a whole have been computed, and these monthly and annual values are given in Table 1, and graphically in Figure 6A.

It will be noted at once that the Gulf and Bermuda areas resemble each other very closely in seasonal temperature-history, while the Caribbean area produces a distinctly different type of curve. The former are characterized by: (a) The relatively large annual range of 10° to 12° F in the water-temperatures; (b) a somewhat larger annual range in the air-temperatures; (c) a very symmetrical rise and fall of the temperature-curves, with maxima and minima approximately six months apart; and (d) the air-temperatures at the minimum falling noticeably below the water-temperatures, but more closely approaching the latter at time of maximum.

Fig. 5-DECEMBER WINDS AND WATER-ISOTHERMS
(Average wind-directions generalized into lines of drift.)
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
73°
74°
75°
72°
71°
70°
69°
68°
73°
74°
75°
76°
77°
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80°
76°
74°
75°

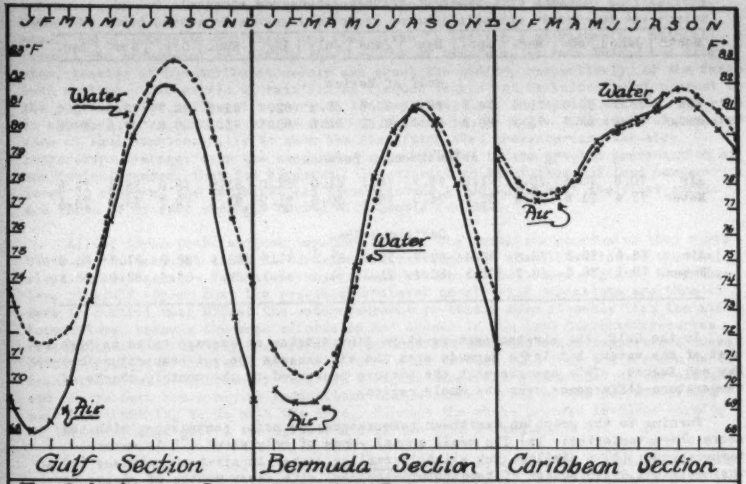
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
Water
Air
Water
Air
Water
Air
Gulf Section
Bermuda Section
Caribbean Section

Fig 6-A—Annual Air and Water-Temperatures, by Sections

Figure 6—Seasonal Curves

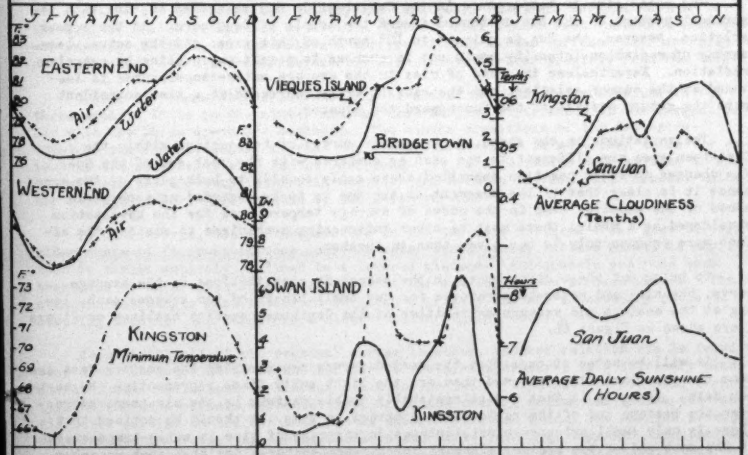

Fig.6-B—Details of Temperature, Rainfall, etc., in Caribbean Section

Table 1--Average air- and water-temperatures in degrees Fahrenheit
(Each area based on sixteen 2.5-degree squares)

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
						Gulf of Mexico						
Air	69.1	69.5	71.0	74.3	77.5	80.8	82.2	82.8	81.8	78.7	73.6	70.4
Water	72.8	72.7	73.1	75.2	77.9	81.2	82.8	83.8	83.1	80.8	77.5	74.8
						Atlantic near Bermuda						
Air	70.8	70.3	70.3	71.8	75.7	79.2	81.0	82.0	81.5	79.0	75.4	72.5
Water	72.4	71.6	71.4	72.2	74.9	78.4	80.5	81.9	81.6	79.7	76.8	74.4
						Caribbean Sea						
Air	78.6	78.3	78.6	79.4	80.7	81.2	81.5	81.9	82.4	82.0	81.2	80.0
Water	79.1	78.6	78.7	79.2	80.4	81.1	81.4	82.1	82.8	82.6	82.0	80.5

In the Gulf, the air-temperature at no time attains an average value as high as that of the water, but in the Bermuda area the air exceeds the sea-temperature between May and August. This accords with the picture presented on the monthly charts of temperature-differences over the whole region.

Turning to the graph of Caribbean temperatures we note, contrasting with the above characteristics: (a) The small annual range of only about 4.5 in water-temperatures; (b) a similar, but slightly smaller, range in air-temperatures; (c) an unsymmetrical distribution of temperature-changes, with seven months of rising temperature and only five months from maximum to minimum; and (d) a distinct retardation in the average rate of temperature-rise after May, as if there were a tendency toward a small secondary minimum about July.

The rapid rise in temperature in the Caribbean in May coincides in time with the vertical passage of the Sun northward toward the tropic of Capricorn. At the summer solstice, however, the Sun is only 5° to 10° north of this area, and the actual lessening of radiation-intensity could not be such as to permit any cooling by outgoing radiation. Nevertheless the rate of rise in the average water-temperatures is lessened at the summer solstice, and the rate is again increased at a time coincident with the return passage of the Sun toward the equator.

The variations in the shape of the summer curves of temperature within the Caribbean area are different in the east as compared with the west end of the Sea. The changes in solar position described above apply equally to both parts of the area; hence it is clear that if the movement of the Sun is to be regarded as a possible cause of the peculiar hump in the curve of average temperatures for the key-section considered as a whole, there must be other intervening mechanisms to distort the effect more pronouncedly in one place than in another.

To bring out these differences in the component contributions to the average curve, the air- and water-temperatures for two small blocks of two squares each, lying at the eastern and western extremities of the Caribbean section outlined on Figure 1 are shown as Figure 6B.

It will be noted at once that the dotted curves representing the western data are more characteristically deformed than are the light solid lines representing the eastern data. There is in fact a distinguishable double maximum in the air-temperature over the western end of the region. In contrast to this, it should be noticed that there is only small evidence of disturbance in the rate of rise in water-temperatures at the east end of the region, although the air-temperatures for that spot reveal a very decided tendency towards a secondary minimum in July. Careful comparison will show that at both east and west ends the air-temperatures are more greatly disturbed during this season of general warming than are the water-temperatures, but also that there is a progressive increase in distortion of all temperature-curves from east to west.

This would point to the conclusion that the proximate source of the disturbing influences is not simply in the passages of the Sun with the seasonal declinations. Hence the added curves of seasonal march in several climatic records of the region should be of interest, and these are also given in section B of Figure 6. Rainfall reveals two pronounced and nearly equal maxima of intensity at Swan Island and Kingston, located at the northwest corner and about the middle, respectively, of the Caribbean section. The curves of rainfall at Vieques Island and Barbados, lying nearest to the northeast and southeast corners of the key-area, lack the spring maximum, but rise in a humped curve toward a single dominant maximum in the fall. The curve of temperature at land stations fails to show the distortion that characterizes the air-temperature averages over the sea; this is exemplified by the graphic presentation of one typical record, that for Kingston. In contrast to the failure of land temperatures to conform, the sunshine- and cloud-records given along with the other curves are shown to be very strongly marked with double maxima.

All of these facts weighed together support the tentative conclusion that variations in the seasonal march of atmospheric events govern the distortion of the rising slope of average air- and water-temperatures within the Caribbean region. Nevertheless it would appear that the result of whatever complicated mechanisms are thus at work in control must affect the water-temperature itself more directly than the air-temperature, because the same effects do not appear in the land temperature-curves representative of the region. Finally, in the fact that the water-temperature curve itself displays progressive distortion from east to west, and that the western Caribbean maintains, from December to July, a higher temperature than that of the eastern end of the Sea, there may be indications that westward drift of the surface-waters also has something to do with the case. Perhaps the whole process involves warming of the water that enters the Caribbean from the open Atlantic.

We have thus been led to tie together the march of events in the atmosphere and the course of surface-water temperatures in the Caribbean. Is it similarly possible to relate these data to the two other regions studied? An approach has been made to the answer to this question.

Summer temperatures in the water-surface reach almost identical maximum values in all three of the key-sections, namely, the Caribbean, Gulf, and Bermuda waters, but the Gulf of Mexico is warmest by about a degree. This latter fact indicates that summer warming continues to accumulate a storage of heat in the surface-water not only as drift proceeds through the Caribbean but also in its further progress into the Gulf.

Summer air-temperatures likewise run to almost the same maximum values in the three areas. It is in the winter minimum that we find differences of the largest order when the three areas are compared. The winter conditions of the two extra-tropical sections evidently depress the temperature-values to more than twice the extent of the seasonal change in the Caribbean. It is significant that at time of winter minimum the air-temperatures in the Gulf and Bermuda regions fall markedly below the average temperatures reached by the water-surface.

In other words, the air-temperature in the two more northern areas goes through a wider range of fluctuation than does the water-temperature, but the excess in amplitude is almost entirely confined to a lowered minimum. Atmospheric controls seem therefore to enter with special effect into the cooling of the surface-waters. The atmospheric changes must therefore be given a primary and not a secondary place in coupling together the temperature-situations during the cooling season.

Considering all of the seasonal curves together, another relation can be found to bear upon the question as to whether air- or water-temperatures take a primary place in the annual variations of thermal state in the two related masses. Careful inspection of the data reveals that the times of annual average maxima and minima come in all cases earlier in the air than in the water. In other words, the changes in water-temperatures generally lag behind those in the air. This lag, together with the noteworthy excess of amplitude in air-temperatures, at least shows conclusively that the water-surface cannot be assumed to have a primary place in the causation of the fluctuations herein discussed.

This does not in the least deny the physical efficacy of the stored heat of the

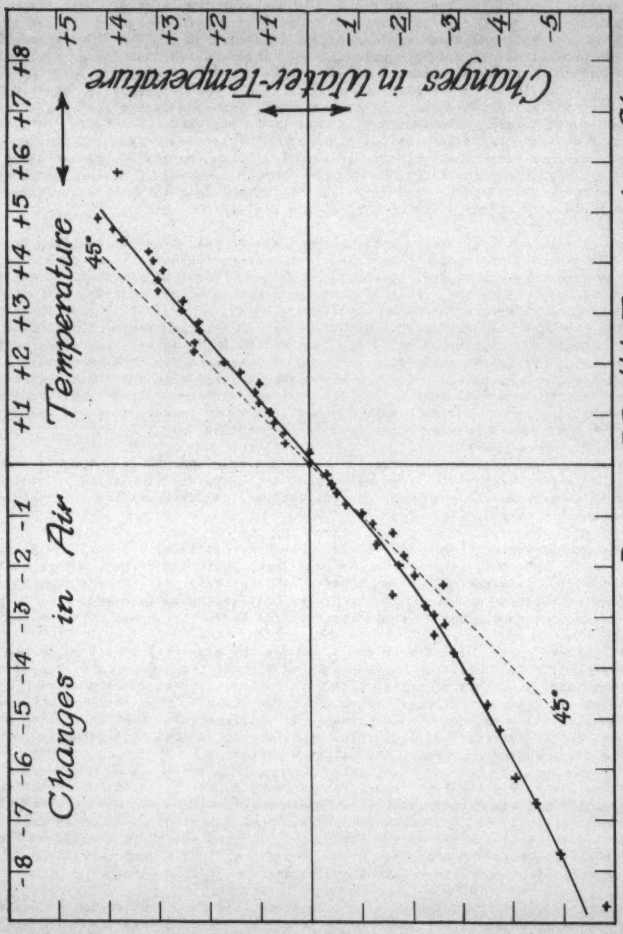

Figure 7–Ratio between Average Monthly Temperature Changes

water-mass acting to damp the range of variation in the air-temperature. Evidently, however, the atmosphere can, by intense outpourings of cold continental air-masses, maintain in the cold season a temperature differential of considerable size even over an extended warm water-surface such as the Gulf of Mexico. A maximum monthly average difference of 6° is shown by our data to prevail in December over many thousands of square miles of the northern Gulf.

Such large differences between cold air and warm water of course result in transfer of heat from water to air. This transfer raises the temperature of the air con-

siderably above its original continental value, but likewise results in lowered water-temperatures.

There remains to be placed in evidence still one other treatment of the data bearing upon the relation between the concomitant variations within the temperatures of each of the two masses represented. The month-to-month changes in temperature were computed within each set of averages for all of the 48 squares included in the three key-sections. These were then grouped into classes based on the amount of change in the air. The average amount of water-change thus computed for each interval of air-change was plotted in a dot diagram (Fig. 7). For example, there were 26 cases of monthly changes in air-temperature between plus 0°7 and plus 0°9; the mean of the corresponding changes in water-temperature was plus 0°7. The average class-value of 0°8 (for air-change) was used as the abscissa and the average value of the concomitant water-temperature changes, 0°7, was plotted as the ordinate of the point.

The computations brought out 52 pairings of mean values, and through their plotted positions a line of approximate best fit was drawn by inspection. To give a basis for estimating the slope of that line, there is indicated in Figure 7 the 45°-line, which would represent complete equality between any two classes of changes depicted by such a chart.

The line of best fit departs considerably from the slope of 45°, however, and in such a way as to indicate that for every rise of 1° in air-temperature there is a rise of about four-fifths of a degree in water-temperature, but in the minus quadrant, which represents falling temperatures, the ratio of water to air-change is diminished to about five-eighths for the larger changes.

From the oceanographer's point of view, the conditions herein discussed will admit of the following specific conclusions:

(1) The situation normally existing over the Gulf of Mexico and western Caribbean favors passage of heat and water-vapor from the water-surface into the overlying atmosphere. This is intensified by winter conditions, and in that season extends in area to the eastern border of the region studied.

(2) During the warm season, there exists over the more eastern portions of the West Indian waters a temperature-situation in which the air is slightly warmer than the water. This must diminish the energy demand upon the water, and favors accumulation of heat in the ocean-surface.

(3) The orders of magnitude and of time in the variations of temperature in the region studied preclude the conclusion that the water-surface can, in that region, initiate the seasonal fluctuations in air-temperature.

Acknowledgment--Appreciation must be recorded for the painstaking work of D. J. Stewlingson in assisting with computation of basic data and in preparation of the charts and figures used.

U. S. Weather Bureau,
Washington, D. C.

OCEANOGRAPHIC RESEARCH AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY, UNIVERSITY OF CALIFORNIA, APRIL 1932 TO APRIL 1933

T. Wayland Vaughan

Introduction

The buildings and equipment of the Institution mentioned in the first part of my report for last year were completed near the end of the summer, 1932, and after that date the increased facilities for research immediately began to bear fruit. The work in chemistry, experimental biology, and the study of marine bottom-deposits have profited greatly during the past 12 months, and evidence of this is shown in the statements which follow.

The general program of the Institution has not changed. Therefore, the topics under which accounts of the researches at the Institution are given remain as they were in the report for last year.

Sources of oceanographic data

As in the past the boat Scripps was used at local stations for taking temperature-observations, for obtaining water-samples for chemical analysis, and for collecting plankton-samples. A number of experiments were made with various types of apparatus for taking bottom-samples and for obtaining at the lower levels water-samples for bacterial examination.

An intensive study of the circulation and the physical and chemical conditions in a submarine valley near the Institution was made. This investigation gave a number of interesting results. For example, the physical and chemical conditions of the water at all or most depths often showed a marked change over a period of a few hours. Sometimes these changes gave evidence of a horizontal movement of the water-mass and sometimes an upward movement. The direction and intensity of the currents in the valley apparently varied with the tide, though in an irregular manner.

A considerable amount of material and data have been obtained and are now being obtained from Naval vessels in cooperation with the Hydrographic Office of the United States Navy. Temperatures and water-samples for salinity-determinations were obtained by the U.S.S. Hannibal on a cruise from Philadelphia to the Canal Zone, and while engaged in survey-work in the Caribbean near Panama, and in the Gulf of Panama in the Pacific. While in the Gulf of Panama, R. H. Fleming of the Scripps Institution was on board the Hannibal and carried out 423 determinations of oxygen at 85 stations, and collected 500 samples for salinity-determinations, 60 bottom-samples, and 60 plankton-samples. On April 10 the Hannibal left for the west coast of Costa Rica where Fleming will continue the same kind of work as was carried out in the Gulf of Panama. It is also hoped that it will be possible to extend the program so as to include determinations of a certain number of plant nutrients. The work off the coast of Central America is considered especially valuable in view of the fact that practically no previous work has been undertaken in that locality and that complex hydrographic conditions obtain there.

The Institution has continued to receive water-samples and records of sea-surface temperatures and meteorological data from the Scripps Institution and Balboa piers, from Pacific Grove, Hueneme, Farallon Islands, Blunts Reef and Columbia River Light Ships, Scotch Cap, and the Lighthouse Tenders Lupine and Rose. The records from the last five sources have been received largely through the cooperation of the Bureau of Lighthouses. Information has also been supplied by the United States Naval Transports, the vessels Guide and Pioneer of the Coast and Geodetic Survey, and the Grace Line ships plying between Valparaiso and Central American ports. The Institution has a water-thermograph installed on its own pier, on the Los Angeles Steamship Company's S.S. Calawaii, which makes fortnightly trips from Los Angeles to Hawaii, and on the U.S. Lighthouse tender Lupine.

The numbers of observations of different kinds are entered in Table 1.

A water-thermograph loaned by the Scripps Institution for a limited trial was installed on the Panama Pacific Company steamer Pennsylvania, plying between New York and San Francisco. A similar instrument, purchased by the Scripps Institution, has been in operation on the steamer California of the same company for more than a year, and the steamer Virginia has been equipped with a water-thermograph for more than two years. All of these thermograph-records will be worked up and filed at the United States Weather Bureau in Washington, D. C., according to arrangements made with the Chief of the Bureau. These records will be loaned for a limited time, in order that copies may be made.

Table 1--Numbers of oceanographical observations listed by Scripps Institution of Oceanography

Element	U.S. Navy transports	U.S. Lighthouse tenders	U.S. C. and G.S. ships	Scripps stations 1 and 2	Shore, La Jolla to Scotch Cap	Grace Line ships[a]	U.S. Navy	Supplementary data Lower Calif.	Total
Salinity	.....	192	(172)	(232)	2,868	.....	(96)	81	3,641
Water-temperature	4,078	800	(282)	(232)	2,975	2,000	(96)	81	10,544
Air-temperature	424	650	.....	.....	365	.....	....	..	1,439
Wind	4,078	900	.....	.....	2,138	2,000	....	..	9,116

[a] Valparaiso to Central American ports.

Note: Where entries are enclosed in parentheses () the observations are subsurface.

Physical oceanography and marine meteorology

G. F. McEwen has charge of the investigation in these fields. The ships' reports of sea-temperatures and winds, from an area of about 50 one-degree quadrangles in the San Francisco Section, 1898 to 1931, inclusive, used to determine monthly averages for selected groups of quadrangles, have been used with other surface-data in the eastern North Pacific for investigating surface-drift and the problem of seasonal weather forecasting.

Summarized serial observations of temperature, salinity, and pH at stations 1 and 2, 10 and 5 miles west of the Scripps Institution's Pier, have been corrected and mimeographed. Values are entered at half-month time-intervals and for 19 depths from the surface to 100 meters. Weekly and monthly averages of all shore-station data have been worked out to date, and mimeographed copies are available for distribution. Blueprints of seasonal curves plotted from weekly averages are also available for distribution. The tabulation of surface-observations at sea according to 30-minute quadrangles and weeks or months has been continued and entries on charts kept up to date.

McEwen has completed the theoretical part of two papers, and work is progressing on applications of the principles to data on hand. One paper presents the results of a re-examination of his theory first published in 1919 on the relation of horizontal drift to sea-surface temperatures and solar radiation. More convenient formulae have been developed and revised values of coefficients have been worked out using later observations with particular reference to the North Pacific. The other paper presents a solution of the differential equation of diffusion or conduction used as a basis for computing vertical velocity and turbulence, and includes appropriate tables for application to ocean-data. Further work is being done in the general field of turbulence suggested by McEwen's paper, published in 1929, on "A mathematical theory of the vertical distribution of temperature and salinity in water under the action of radiation, conduction, evaporation, and mixing due to the resulting convection." In connection with seasonal weather-forecasting, he has developed a method of forecasting monthly surface-temperatures at the Scripps Institution's Pier.

A good deal of interest has been shown relative to our investigations of seasonal weather-forecasting. Forecasts of seasonal precipitations at La Jolla during the midsummer upwelling-period correctly indicated an excess or deficit in practically three-fourths of the years from 1923 to 1931, but the divergence of computed and observed values in 1931-32 pointed to the need of a broader and more flexible index. Studies of the correlation between the precipitation or runoff and the ocean-temperatures of various months showed that a better fit might be secured by using values for certain months preceding as well as following the summer period.

The computations were performed by the ordinary least-squares method (Doolittle

solution), also by a related method in which the element predicted is expressed as a joint function of two temperature-factors.

These new formulae resulted in a much better verification than previous ones, when applied to the chief rainfall and runoff areas in Northern California. For the Huntington Lake district rainfall, and the Owens River runoff, an agreement of sign of the departures was noted in 13 years out of 16. When air-temperatures at San Diego were substituted for ocean-temperature at La Jolla, as an index, the error increased by several per cent, probably on account of the inherently variable nature of the former.

Investigations of possible weather-cycles have been continued, and evidence has accumulated in favor of certain cycles, that is, five and one-half years, and the longer Brückner cycle of about 30 years. Data on air-temperature, precipitation, stream-flow, and lake-levels in both North and South America have been used by Gorton in these studies.

H. R. Byers' study of the air-mass of the North Pacific, which was begun a year ago, has been continued and is practically finished. The past year has been devoted chiefly to a detailed analysis of all available free data, including soundings by aeroplane made by the United States Navy at San Diego (California), Sand Point (Washington), and Pearl Harbor, Territory of Hawaii, and sounding-balloon data from Batavia. In addition, the Scripps Institution with the aid of the Astrophysical Observatory, California Institute of Technology, conducted a series of aeroplane-soundings in the Los Angeles area during February and the first two weeks of March 1933. Free-air wind data obtained from pilot-balloon observations at stations in and bordering the Pacific have been analyzed in detail. The data have all been studied in accordance with the principles of the Norwegian school of meteorology. Careful analyses of synoptic charts of the North Pacific have been made for a three-and-one-half year period.

Burt Richardson continued his studies of radiation, including the penetration of light into sea-water, and N. W. Cummings, in a week's time available, completed checking the routine salinity-determinations by the gravimetric method in use at the Scripps Institution, and he found them to be satisfactory (error 0.02 o/oo). Routine chlorine-determinations usually agreed with gravity-methods within the same error.

During the year eight papers were published and eleven more were prepared for publication by the members of this section of the Institution's work.

Chemistry

The investigations in chemistry, which are in charge of E. G. Moberg, have consisted mainly of analyzing sea-water for various substances determined in former years and of reducing and preparing for publication the analytical data previously obtained. Among the substances involved in this work may be mentioned oxygen, hydrogen-ions, carbon dioxide in its various forms, ammonia, nitrate, phosphate, nitrite, silicate, calcium, boron, and chloride.

From information available at this Institution and in the literature relative to the quantities of carbon dioxide, titratable base, and hydrogen-ions, and from the results of boron-determinations made here, a study of the buffer-mechanism and of the dissociation-constants of carbon dioxide in sea-water has been made in collaboration with D. M. Greenberg and R. R. Revelle. It has been found that the behavior of the buffer-system in sea-water is markedly modified by the boron compounds, which occur in quantities equivalent to about 4.5 mg of boron per liter. It has been shown that in sea-water the second dissociation-constant of carbonic acid apparently changes with pH and this change has been attributed to the presence of boron compounds.

The recognition of the rôle played by boron in the buffer-mechanism of sea-water has been of importance in the work carried on by R. H. Fleming and R. R. Revelle on the solubility of calcium carbonate in sea-water. The results of repeated experiments, in which aragonite was precipitated from sea-water by raising the pH by the removal of CO_2, confirmed the opinions of previous investigators that, under tropical conditions of temperature, sea-water of pH about 8.20 is saturated with calcium carbonate. The

activity-coefficient of the calcium-ion in water of salinity 35 parts per thousand is found to be about 0.3. Equilibrium is attained very slowly and precipitation in supersaturated sea-water may continue for months. The principal factor in the mechanism seems to be pH, which in turn is controlled largely by the carbon-dioxide content. Salinity and temperature within certain limits are of minor importance.

It has previously been reported that the manometric blood-gas apparatus of Van Slyke has been adapted to the determination of the total carbon dioxide in sea-water. During the past year attempts have been made to determine also the oxygen-content by this apparatus, but, so far, the results have been less accurate than in the case of carbon dioxide, principally because the maximum oxygen-content of sea-water is only about one-tenth that of the carbon dioxide.

During the summer Max Greenberg, a student in biochemistry at the University of California, made a study of the applicability of a new colorimetric method for determining silica of sea-water. In this method the chief reagents are ammonium molybdate and amino-napthol-sulphonic acid. It was found to be more sensitive than the method of Dienert and Wandenbulcke, the one now commonly used, and consequently more suitable for surface-water where the silica-content is too low to give a good test with the old method. However, it was necessary to dilute the deep samples in order to reduce the intensity of the color.

At the present time an investigation of the distribution of oxygen and of certain nutrients in the Gulf of Panama and off the west coast of Costa Rica is being carried out by R. H. Fleming on board the United States Navy survey-vessel Hannibal. The results so far indicate an upwelling of subsurface-water in the Gulf of Panama and the oxygen-data agree in general with those previously obtained by the Dana and by the Carnegie in the same region.

During the early part of 1932 H. W. Graham of the Carnegie Institution of Washington spent several months at the Scripps Institution analyzing the chemical data obtained on the last cruise of the Carnegie and preparing reports on these data for publication. In collaboration with Noberg, six manuscripts were prepared dealing with various phases of the chemical work carried out by the Carnegie.

During the year seven papers on work done in the chemical laboratory of the Institution were published and 12 more were prepared for publication.

Biology

Marine microbiology--These investigations have been in charge of C. E. ZoBell. Assisted by Mrs. Catherine B. Feltham, he has studied variations in the bacterial population as influenced by depth, distance from land, sunlight, tides, ocean-currents, water-temperature, and rainfall. Though informative, these determinations will have to be continued for several years before definite conclusions can be formulated because of the multiplicity of complicating factors. The typical marine conditions in the vicinity of Scripps Institution proves that this location is almost ideal for studying marine microbiology. At least 73 different pure cultures of bacteria and actinomyces have been isolated from sea-water or bottom-deposits and characterized. Studies on the cultural requirements show that marine bacteria are quite unlike fresh-water bacteria, indicating the existence of specific marine bacteria which are foreign to other habitats.

ZoBell has investigations in progress on the rôle of bacteria and related micro-organisms in the nitrogen-cycle in the sea. The distribution, relative abundance, and factors which influence the activity of nitrogen-fixers, ammonifiers, nitrifiers, denitrifiers, and urea-splitters have been considered. Insolation and ultra-violet radiations were found to influence nitrification in sea-water. Sampling devices have been improved.

Mrs. Thelma Wells has been making corresponding observations on the distribution, characteristics, and physiological activities of yeasts and molds. Nutrient media and special methods for studying marine fungi have been developed. Results indicate that yeasts and molds are less numerous than bacteria, but they play an important rôle in the decomposition and transformation of organic matter in the sea.

Over 50 different pure cultures of molds, and four of yeasts have been isolated from sea-water and bottom-muds.

Since December 1, 1932, Miss Esther Allen has been investigating the occurrence of micro-organisms on submerged surfaces by direct microscopic observation. Preliminary experiments indicate that bacteria and to a lesser extent actinomyces and diatoms precede by several hours or even days the attachment of barnacles, hydroids, bryozoa, and other organisms. This direct method of observing the microbial flora which adheres to submerged slides offers another approach to the study of marine bacteria. Already several bacterial types have been noted which have not been recovered by concurrent cultural methods. Bacteria have been isolated which are definitely thigmotrophic. The cause of their antecedence over fouling organisms on submerged surfaces is now receiving attention.

During the year two papers were published and two papers were prepared for publication by the members of this section of the Institution's work.

Phytoplankton and the fouling organisms--W. E. Allen and Miss Easter E. Cupp have been engaged on work as follows:

(1) Computations and tabulations have been completed for the total diatoms in the ten-year series of daily collections of phytoplankton at southern California piers, and several graphs have been finished. Progress has been made on similar treatment of a single species, Nitzschia seriata Cl., and a part of the work on dinoflagellates in the same series has been done.

(2) A report on the catches by the boat in 1928 has been finished.

(3) Studies of the species characters of plankton-diatoms and the ranges of variations in specific characters have been continued, and several hundred drawings with notes on geographic and seasonal conditions having influence on abundance and character of growth have been added during the year.

(4) Pier collections of phytoplankton in the southern California region, daily for 14 years, are being continued, although series in other regions are being closed. The Institution's Pier seems to yield fairly representative evidence concerning annual, seasonal, or other gross cyclical and periodic fluctuations in fundamental conditions of existence of organisms in the Gulf of Santa Catalina.

(5) Cooperation with W. R. Coe of Yale University in studies of "fouling organisms" has been continued. Allen has devised improved apparatus for suspending collecting plates in the sea while organisms are growing on them. Allen has conferred with C. E. ZoBell concerning the initiation and progress of experiments by Miss Esther C. Allen, under ZoBell's direction, on the formation of films or deposits on submerged surfaces in the first 24 to 48 hours.

(6) A report has been finished on a small series of surface collections of phytoplankton (mainly diatoms) taken between San Diego and the Galapagos Islands by the Templeton Crocker Expedition of the California Academy of Sciences.

Three papers on the work listed above are in preparation.

Foraminifera--T. Wayland Vaughan, assisted by W. Storrs Cole and Donald W. Gravell, completed a number of papers on Tertiary and Cretaceous larger foraminifera from the Gulf States, Mexico, the West Indies, Central America, and northern South America. Five papers were published during the year and three are awaiting publication.

Earl H. Myers has been making extensive cultures of species of foraminifera found in the vicinity of the Institution. The status of his researches is embodied in the following statement:

Specimens of the pelagic Tretomphalus bulloides, the adult stage of the bottom-dwelling Discorbis globularis, have been observed almost daily throughout the winter in cultures started August 16, 1932. The last Tretomphalus from the sea were collected

November 10, 1932. No other specimens have reappeared to date, April 10, 1933. During the pelagic Tretomphalus stage, the individuals discharge their cargoes of zoospores from three to 23 hours after appearing at the surface. The empty test usually remains afloat during the second day. At times due to extraneous reasons, tests have been known to remain afloat for weeks. This may account for records of Tretomphalus in latitudes where the temperature is too low for its normal development (the thermal requirements for this metamorphosis can and will be checked experimentally). It is interesting to note that culture-conditions which have proven favorable over a period of months for the development of the above-mentioned stage have failed to give any indication of the fate of the thousands of zoospores liberated in the same containers. Methods have been devised and equipment purchased that should give a positive answer to the normal fate of these so-called zoospores.

Patellina corrugata in cultures exhibits two methods of reproduction, first by producing viviparous young and second by plastogamy, in which the protoplasms of from two to five individuals unite to form a common mass, that later gives rise to young similar in all respects to the viviparously produced young above mentioned. The cytological observations on this form agree in all respects with those of Schaudinn.

Discorbis patelliformis also produces viviparous young. Two or three individuals of this generation when about two-thirds grown fuse as in Patellina, and in a few instances have produced young similar to the parents. However, the great majority of paired tests are completely filled with tri-flagellated organisms within 12 hours of the time the tests have fused. This observation has been made hundreds of times, over a period of three years. Many cytological preparations have failed to give any conclusive evidence as to the origin of these flagellates. Efforts to rear these zoospores (?) on either solid or liquid media have not yet been successful. Budding as a method of reproduction reported by Heron-Allen and others, and based on poor circumstantial evidence suggested undoubtedly by reported observations on certain monothalmous forms, does not occur in the rotaliform species.

Discorbis sp. has been in culture for two years. Pedigreed cultures of this species have been maintained for nine consecutive generations. Under optimum conditions individuals will mature and reproduce in from 21 to 35 days. It is not uncommon to isolate, at one time from a single dish, as many as 2,000 one-day-old young. The first day the three chambered viviparous young remain clustered closely under the parent test and may be easily removed with a pipette.

Spirillina vivipara is readily cultured if the specimens are periodically washed with a stream of water. This is necessary to prevent the substrate of diatoms and bacteria from choking out the foraminifera. A few small gastropods help to maintain a clean substrate. Patellina must be handled in the same manner.

Triloculina circularis is not so prolific as Discorbis sp., but many thousands have been reared over a continuous period of two years. Only the megalopsheric stage occurs in culture.

Calcituba polymorpha has been cultured from the original stock culture for more than two years and sub-cultures are easy to make and maintain. Schaudinn's observations on this species have been neither substantiated nor contradicted.

Bulimina sp. in cultures over a period of two years has reproduced by the thousands. Only one stage occurs and no plastogamy has been observed.

Elphidium crispa reproduces asexually in material recently removed from the sea and will live in culture-dishes in a semi-dormant state for 18 months or more, but high temperatures and other unfavorable culture-conditions prevent normal development of the young. Observations on individuals in cultures agree with Lister's in that the protoplasm gradually recedes from the distal chambers and the nucleus is reduced in size. Schaudinn stated that Elphidium will not reproduce at temperatures above 18° C.

Planulina ornata has failed to remain active in cultures.

Fishes--A summary of the work of F. B. Sumner and his associates during the past year is as follows:

(1) Effects of visual stimuli received from the background upon the formation and elimination of melanin pigment in fishes. In addition to the well-known rapid changes of shade resulting from pronounced changes in the background, it was found that slower changes occur in the number of melanophores and the amount of pigment in each. Such adjustments were not found to be irreversible, however, even in the case of fishes kept for several generations on the same background, when the latter was lighted throughout the entire 24 hours. (Paper by Sumner and Wells, Jour. Exper. Zool., Feb., 1933.)

(2) Determination and quantitative estimation of carotenoid ("lipochrome") pigments, and experiments upon the possible influence of optic stimuli upon these (Sumner and Fox). The colored pigment present in all of the three fishes studied was found to be a xanthophyll ($C_{40}H_{56}O_2$). Except in one instance, the actual amount was not affected by the background, despite pronounced changes in the visible coloration of the fish. In the case of one species, however, a sojourn of three to four months on white resulted in a great reduction in the amount of xanthophyll. The food, a worm containing carotene, not xanthophyll, was constant for all.

(3) Relative effects of different portions of the visual field upon the color reactions of fishes. This is a continuation by Sumner, with recently devised technique, of a line of investigation commenced by him as early as 1910.

H. A. Wells, research assistant of Sumner, has continued his studies of effects of temperature, size, sex, season, etc., upon the oxygen consumption of fishes, a continuation of the work of the past two years, with methods earlier standardized, but variously applied to different related problems. Despite numerous technical difficulties, a number of highly significant correlations have already been revealed. He has shown that fishes may not attain a normal rate of metabolism for many hours after their introduction into an experimental environment (Proc. Nat. Acad. Sci., Sept. 1932).

During the year two papers were published and three are in preparation in this section of the Institution.

Physiology

Physiology--The investigations in this field are in charge of Denis L. Fox. During the summer of 1932, Fox, in conjunction with Florence Peebles of the California Christian College at Los Angeles, studied the morphology, general reactions, and physiological adaptations of the marine sipunculid worm, Dendrostoma zostericola Chamberlin. Special attention was given to the intake of sand containing organic matter, the rôle of the cerebral ganglion and nerve-cord in burrowing reactions, the location and sensitivity of various sense-receptors, and the high degree of adaptation toward desiccation and toward oxygen-deficiency. Results of the investigation will soon appear in the Bulletin of the Scripps Institution of Oceanography.

H. F. Blum, of the Physiology Division of the University of California, and Fox studied the light-responses in the brine flagellate Dunaliella salina with respect to wave-length of incident light. They found in both the red and green modification of the species, an equal maximum sensitivity to light of wave-lengths between 480 and 530 mμ. The positive phototaxis of either phase is limited to a spectral region between 330 and 550 mμ. The results were published in the University of California Publication (v. 8, No. 3, 21-30, Feb. 1933).

Fox and G. W. Marks have been investigating the hydrogen peroxide decomposing enzyme, catalase, in the California mussel, Mytilus californianus Conrad. They have completed one rather intensive piece of work and have another investigation nearly completed. The concentration of catalase was, in general, greater in glandular and highly vasculated tissue, and lower in muscular tissue. Extracts of young animals showed considerably higher catalase activity than those of older individuals. Mussel catalase is apparently inactivated in the presence of atmospheric oxygen. The optimum hydrogen-ion concentration for catalase activity is very close to pH 7. There is a sharp drop on the acid side of the optimum, but only a gradual sloping off on the alkaline side to about pH 8.5. The latter fact would lead one to suppose that the hydrogen-ion concentration found in the ocean where the animals were collected is favorable for the adequate performance of this vitally important enzyme within the animal, the pH of whose tissues is certainly close to that of sea-water. Temperature-

studies showed an optimum catalase activity between 0° and 10° C for 30-minute periods. It has been shown that, up to certain concentrations of the enzyme, the quantity of hydrogen peroxide decomposed is directly proportional to the catalase concentration, and independent of the concentration of the substrate. This finding is in agreement with those of investigators who worked with other catalases.

The velocity-constant for the inactivation of mussel catalase by oxygen is that of a first-order reaction, but since oxygen is one reactant, the reaction must be at least bimolecular, and the pseudomonomolecular character must be the result of a greatly excessive concentration of oxygen over that of catalase. The reaction-rate constant for the inactivation of catalase was determined accurately at several different temperatures, and the Arrhenius equation for the change in the reaction-rate constant with temperature was shown to be applicable.

The investigations of the carotenoid pigments of fishes, jointly with Sumner, have been mentioned.

During the year this section of the Institution published two papers and three papers were prepared for publication.

Marine sediments

In my report to the Section last year I made a fairly full statement of the program of work on marine sediments at the Scripps Institution. Therefore, what is now needed is only an account of developments which have taken place since that report was made.

The importance of the investigations of the buffer-mechanism of sea-water to problems of sedimentation is indicated in the section of this report which deals with the chemical investigations conducted at the Institution during the past year. The manuscript by Greenberg and Moberg and Miss Esther Allen, which was finished a year ago, was not immediately sent to press because the authors were not satisfied with some of the details. The determination of the amount of boron in sea-water by M. W. Harding led to a re-study, both theoretically and by means of laboratory experiments, of the effect of boron on the buffer-mechanism of sea-water. The paper has been revised by Moberg and Revelle and is ready for publication. This paper, in my opinion, represents the most satisfactory treatment which the very intricate problems concerned have yet received.

Although the study of the life history of foraminifera may seem remote from the investigation of marine bottom-deposits, it is really a very closely related subject. Foraminifera are probably the most important group of organisms which contribute material to bottom-deposits. For this and other reasons, such as the knowledge of taxonomy of the group and of the means whereby geographical distribution is effected, it is highly important that we should understand the life history of these organisms. Therefore, although Myers, in his study of the life history of foraminifera, is utilizing strictly biological methods in his investigation, he is also contributing information of value to those who are interested in the geological aspects of the sea.

E. M. Thorp has continued his study of the calcium carbonate bottom-deposits of the Florida-Bahamian region and has virtually finished his description of the samples. In order to get a basis for additional comparisons of such deposits in the Floridian and Bahamian region with deposits in the tropical and sub-tropical Pacific, a study has been made of a series of samples collected by P. S. Galtsoff on Pearl and Hermes reefs, Midway Islands, of the Hawaiian group. A report on these samples is nearing completion.

It was mentioned last year that the deep-sea samples collected by the Carnegie during her work in the Pacific were being studied at the Scripps Institution by Roger Revelle. The following statement gives the present status of the investigation.

The general examination and description of those Carnegie samples which have been mechanically analyzed have been nearly completed. Of the 46 samples which have thus been examined there are 20 globigerina oozes, 13 red clays, 3 diatom oozes, 2 radiolarian oozes, 2 volcanic muds, 3 coprolitic muds, and 1 blue mud. The method of ex-

amination has consisted in identification of the various organic and mineral components of the samples and in the estimation of their relative abundance. Attention is now being paid to specific problems which have arisen in connection with this study such as the determination of the clay and other minerals in the silt and clay grades; identification of heavy minerals, volcanic glass and rock fragments; further mechanical analyses of the fine grades; correlation of chemical and optical analyses; possible dolomitization of the shell fragments in the samples; and mode of alteration of volcanic glass.

One of the interesting results which has been obtained from the study has been the definite identification of the clay mineral in the red clays of the North Pacific as a member of the beidellite-montronite series in which the ratio of SiO_2 to R_2O_3 is as 3 to 1. In this series for a part of the Al_2O_3, Fe_2O_3 is substituted. C. S. Ross kindly checked this determination.

Heavy-mineral analysis of a series of five samples from the northwest Pacific, off the coast of Japan, indicate that the bottom-deposits of this region are derived in part from the products of Japanese volcanic eruptions. Although two of these samples are classified as volcanic muds and three as diatom oozes, all are nearly identical in chemical composition. The percentage of heavy minerals, however, decreases uniformly from the coast of Japan, while the percentage of diatoms and radiolaria correspondingly increases.

Another feature of interest is a group of three samples from the southeast Pacific which have been called coprolitic muds. Two of these, judging by their chemical composition, distance from shore, and depth, would be classified as globigerina oozes were it not for the numerous ellipsoidal and disk-shaped aggregates of fine material which they contain, and for the fact that the larger part of the unbroken foraminiferal shells are those of benthonic genera. The percentage of $CaCO_3$ in both of these is close to 42 per cent. The third sample has only 3 per cent $CaCO_3$, but is similar in other respects. Pellets similar to those found in such abundance in these three samples have been observed as minor constituents of numerous others.

The foregoing statements regarding the work of Thorp and Revelle need to be supplemented. Thorp has already published a paper entitled "Descriptions of deep-sea bottom-samples from the western North Atlantic and the Caribbean" (Scripps Inst. Bull., tech. ser., v. 3, No. 1, 1-31, 1931). After this report had been published it seemed desirable to utilize recently developed X-ray methods to see if the X-ray patterns would make possible the recognition of the minerals represented in the very fine fractions of the sediments. Obviously it was also desirable to have the X-ray investigation include the fine fractions of the deep-sea sediments from the Pacific. We were fortunate in enlisting the assistance of W. H. Dore, Division of Plant Nutrition, College of Agriculture, University of California. Accordingly, a set of samples representing both the deposits in the Atlantic and the deposits in the Pacific were prepared for him. He has already made X-ray exposures of 28 samples and has prepared 56 films. The results have been illuminating but there has been difficulty in interpreting all of the films. Therefore, Dore has undertaken to make X-ray spectrograms of a series of selected mineral standards. Already spectrograms have been made of 13 specially selected mineral species. The work has not yet been finished, but it is progressing and the prospects are good for achieving results of value.

Another line of investigations of deep-sea sediments has been made possible through the generous cooperation of George Steiger of the United States Geological Survey. He undertook to make spectrographic analyses of 100 deep-sea samples and has actually reported on 101 samples. His report includes determinations of B, Ba, Be, Bi, Ge, Sn, and Zn. In his report he says that besides tests for the six metals shown in the accompanying report D 225, plates were made including spectra which will make it possible to examine these same plates later on for Ag, As, Cd, Pb, Sb, Li, and Sr. Additional study of the plates made to see if the elements mentioned by Steiger may be recognized will be attempted. He has submitted a very interesting discussion of the significance of the varying amount of barium in the different samples.

With reference to the Carnegie samples, it may be stated that mechanical analyses of the samples of which the quantity was sufficient were made at the Scripps Institution. Chemical analyses of a selected set of samples were made by Sharp-Schurtz Com-

pany. In addition to the different kinds of examinations above indicated, C. S. Piggot of the Geophysical Laboratory of the Carnegie Institution of Washington analyzed some of the samples for radium, and Parker D. Trask analyzed a set of samples for the organic content. It, therefore, seems that by combining the different lines of work above indicated we shall have as complete information on the Carnegie deep-sea samples as is at present practicable.

During the year four papers were published and four more are being prepared for publication by the members of this section of the Institution's work.

Scripps Institution of Oceanography,
University of California,
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OCEANOGRAPHIC RESEARCH AT THE UNIVERSITY OF WASHINGTON FOR THE YEAR 1932

Thomas G. Thompson

Since our last report, our research boat Catalyst has been completed and put into service. The boat is 75 feet in length, with an 18-foot beam. It has a 120-horsepower Washington-Estep engine with a 9-horse-power Lister diesel generator, and has a cruising radius of 3,500 miles. It is equipped with the necessary apparatus for taking samples to a depth of about 4,500 meters. The boat is also equipped for dredging to a depth of 800 meters. The laboratory, which is 18 by 10 feet, occupies part of the main deck space and has facilities for work in physical and chemical oceanography and marine biology, each desk being supplied with gas, alternating- and direct-current, with arrangements for the use of variable voltage. Since the boat has been put into commission, we have covered some 7,000 miles in Puget Sound, off the Washington coast, and in the waters of southeastern Alaska.

The Oceanographic Laboratories on the campus on the shore of Lake Union were dedicated last June and are in full operation. At the present time there are about 50 people working in the Laboratories, including members of the staff and their graduate students.

Attached are listed papers published during the past year, papers completed and either submitted or ready to be submitted for publication, and projects under way at the present time.

Mention should be made of the work of the committee of oceanographical chemists composed of representatives from the four laboratories on the Pacific Coast, namely, Scripps Institution of Oceanography of the University of California, Hopkins Marine Station of Stanford University, Oceanographic Laboratories of the University of Washington, and the Pacific Biological Station of the Fisheries Board of Canada. Recommendations on the reporting of chemical data have been made in order to insure uniformity which will facilitate interpretation and comparison, particularly of the data along the Pacific Coast of North America.

Our Laboratories are grateful for the cooperation we have received from the United States Coast Guard, the United States Coast and Geodetic Survey, and the United States Navy. The Laboratories are cooperating with the United States Navy in a survey of the Alaskan waters, and in our next report we hope to give considerable information concerning the currents calculated for dynamical sections, together with information on the dissolved oxygen, silicates, etc., of the waters off the Aleutian Islands, both in the North Pacific and in Bering Sea.

I have been asked to serve on a subcommittee under the main Committee on Oceanography of the National Academy to report on the teaching of oceanography. A report of progress and a preliminary report have been submitted to the chairman of the main committee.

Published papers

Variations in visible solar radiations. C. L. Utterback. Science, 77, 1987 (1933).
The radioactivity of sea-water. D. Devaputra, Thomas G. Thompson, and C. L. Utterback. J. du Conseil VII, 3, 358 (1932).

Occurrence and determination of iron in sea-water. Thomas G. Thompson, Raymond W. Bremer, and I. Marion Jamieson. Ind. Eng. Chem. Anal. Ed., v. 4, 288 (1932).
The physical properties of sea-water. Thomas G. Thompson. Bull. National Res. Council, No. 85, 63-94 (1932).
Chemistry of the sea. Thomas G. Thompson and Rex J. Robinson. Bull. National Res. Council, No. 85, 95-203 (1932).
Determination and occurrence of fluorides in sea-water. Thomas G. Thompson and Howard J. Taylor.
A new genus and species of Monorchidae. John E. Guberlet and L. C. V. Lloyd. Jour. Parasit., v. 18, 232-239 (1932).
Notes on some Onchocotylinae from Naples, with a description of a new species. John E. Guberlet. Pubblicazioni della Stazione Zoologica di Napoli, v. 12, 3, 322-336 (1932).
Notes on birds observed at sea off the North Pacific Coast. John E. Guberlet and Robert C. Miller. Murrelet, v. 14, 7-8 (1933).
A study of the antimony trichloride color-reaction for vitamin A: V. Evaluation of a colorimetric unit on the basis of the biological unit for vitamin A. J. Nutrition, v. 5, 495 (1932).

Papers submitted or ready to be submitted for publication

Submarine illumination. C. L. Utterback.
Penetration of solar radiations into the waters of southern Alaska. C. L. Utterback.
Penetration of solar radiation into the waters of Puget Sound. C. L. Utterback and J. W. Boyle.
Periodicity of diatom growth in the San Juan Archipelago. Lyman D. Phifer.
Distribution of dissolved oxygen in the North Pacific. Thomas G. Thompson and B. D. Thomas.
Carbon dioxide and non-volatile weak acids in sea-water. Thomas G. Thompson and Iver Igelsrud.
Report on distribution of phosphates in Puget Sound area and off the coast of Washington. Thomas G. Thompson, R. J. Robinson, Iver Igelsrud, and C. Barnes.
Observations on the spawning and development of some Pacific annelids. John E. Guberlet.
Observations on the hydrogen-ion concentration and temperature in surface-waters of various seas. Robert C. Miller.
Seasonal settlement of shipworms, barnacles, and other wharf-pile organisms in the Puget Sound area. Robert C. Miller.
The arterial system of Eulamia dussumieri (Müller and Henle). Robert C. Miller.
The nervous system of Eulamia dussumieri. Robert C. Miller.
Some properties of kelp colloids. George B. Rigg and Bernadine Dunsford.
Photosynthesis in marine algae. George B. Rigg and Robert H. Tschudy.
Behavior of colloidal particles in living kelp-cells under a direct electric current as seen with a dark field. George B. Rigg and Bernadine Dunsford.
Report on the free ammonia, albuminoid nitrogen, and organic nitrogen in the waters of the Puget Sound area during the summers of 1931 and 1932. Rex J. Robinson and Henry E. Wirth.

Research in progress

Radioactivity of sea-water. C. L. Utterback.
Radioactivity of material from the floor of the sea. C. L. Utterback and L. A. Sanderman.
Refractive index and chlorinity of sea-water. C. L. Utterback and Thomas G. Thompson.
Electrical conductivity and refractive index of sea-water. B. D. Thomas, Thomas G. Thompson, and C. L. Utterback.
Determination of density of sea-water. Henry E. Wirth, Thomas G. Thompson, and C. L. Utterback.
Physical and chemical properties of the waters of the San Juan Channel. Thomas G. Thompson and Lyman D. Phifer.
The physical and chemical properties of the waters of East Sound. Thomas G. Thompson and Lyman D. Phifer.
Diatoms in the Strait of Juan de Fuca, Washington coast, and southeastern Alaska. Lyman D. Phifer.
Seasonal distribution of diatoms in San Juan Archipelago. Lyman D. Phifer.

Seasonal distribution of diatoms in East Sound. Lyman D. Phifer.
Salt deposition by the freezing of sea-water. Thomas G. Thompson and Iver Igelsrud.
Distribution of phosphates, silicates, nitrates, nitrites, and iron in the waters of southeastern Alaska. Thomas G. Thompson, Ray W. Brenner, and Clifford A. Barnes.
Distribution and interrelation of marine fauna of Puget Sound and North Pacific. John E. Guberlet.
Further studies on the spawning and development of Pacific annelids. John E. Guberlet.
Studies on onchocotyle-parasites of elasmobranch fishes. John E. Guberlet.
Zooplankton studies in Puget Sound and adjacent water. Robert C. Miller.
Zooplankton of the cruise of the Catalyst to southeastern Alaska, summer of 1932. Robert C. Miller.
Distribution and speciation of Puget Sound Naticidae. Robert C. Miller.
Digestion of cellulose by lamellibranchs. Robert C. Miller.
Physical factors affecting reproduction of unicellular organisms. Robert C. Miller.
Histology of the selachian labyrinth. Robert C. Miller.
Distribution of Teredinidae about the Pacific rim. Robert C. Miller.
Work on enzymes in marine algae. George B. Rigg and assistants.
Work on red pigments in salt marsh plants. George B. Rigg and assistants.
Work on colloids in kelps is being continued. George B. Rigg and assistants.
Determination of organic phosphorus in sea-water. (Further observations on a method for the determination of organic phosphorus in sea-water are being made.) Rex J. Robinson and Lyle Anderson.
A seasonal study of the chemical and biological nature of Lake Washington. Rex J. Robinson, Trevor Kincaid, and V. Scheffer.
Investigations bearing upon the biology of the oyster, more particularly in connection with the transplanted Japanese species (Ostrea gigantea). Trevor Kincaid.
Studies of the shrimps of Puget Sound. Trevor Kincaid and Belle A. Stevens.
Distribution of the tintinnoid Protozoa in the North Pacific. Trevor Kincaid and Paul Thompson.
Continuation of the study of the $SbCl_3$ reaction. E. R. Norris.
Study of the enzymes of digestion and metabolism of marine invertebrates. E. R. Norris.
Study of the arsenic content of some marine animals of Puget Sound. E. R. Norris.
Quantitative and qualitative bacteriological survey of Puget Sound area. B. S. Henry.
Rôle of NO_2 and NO_3 producing bacteria in the NO_3-content of sea-water. B. S. Henry.
Intestinal flora of marine invertebrates with special reference to cellulose digestion. B. S. Henry.
Anaerobic fermentation in sea-mud. B. S. Henry.
A study of a bacterial disease of salmon. B. S. Henry.
Studies on gregarines of the barnacles of the Puget Sound region. D. Henry.
Studies on gregarines in other marine animals of Puget Sound region. D. Henry.

Oceanographic Laboratories,
University of Washington,
Seattle, Washington

OCEANOGRAPHIC WORK AT THE HOPKINS MARINE STATION, STANFORD UNIVERSITY, FOR THE YEAR 1932

Tage Skogsberg

While in the first three years the work carried out by the Hydrobiological Survey of Hopkins Marine Station was limited to the waters quite close to the Station, in 1932 our program was considerably extended on account of better boating facilities. The entire bay was included in our program and particular emphasis was placed on ascertaining the rôle played by the deep channel in the general hydrographical changes characteristic of the Bay.

Seven stations were established: One was on the northern side of the channel; two were on the southern side; the remaining four, in a manner, triangulated the central channel. Weather and other conditions permitting, these stations were visited once a week. All of these stations except one were limited to the upper 100 meters. One extended down as far as 900 meters. At the 900-meter station water-samples, as well as temperatures, were taken, while at the shallower stations only temperatures were observed.

The total number of temperatures taken during the year amounted to 3,798; Cl was determined for 916 samples, SiO_2 for 899 samples, and PO_4 for 891 samples.

The data are now being worked over. Although the analysis has not yet been completed, it can be said that apparently the channel plays much less of a rôle than had hitherto been assumed. On some occasions during the early summer the upwelling-phenomena were slightly more pronounced at the inner end of the channel than on the northern and the southern sides; but this state of affairs was apparently decidedly irregular, and so far we have not been able to establish the cause of these variations. To all appearances the upwelling, in most cases, affects only the upper 250 meters, although on rare occasions a similar trend of the hydrographic changes may be traced down to 500 meters or even to 900 meters. The deeper strata apparently are less subjected to an updraught than to a decided horizontal drift evidenced by the fact that the temperature-conditions even at 900 meters are constantly changing throughout the entire year. Whether this horizontal drift is predominantly from the northern or the southern side, we have not yet been able to establish. The upper strata are affected not only by the upwelling-phenomena during the early part of the year, but also in a striking manner by a coastwise horizontal drift. This is particularly striking during the last two months of the year, when warm water is carried from the south by the Davidson Current and occasionally accumulates to a relatively great depth in the Bay.

A remarkable phenomenon worthy of special mention occurred during the early fall of 1932. Water of temperatures higher than observed before drifted into the region carrying with it the albacore, which for the first time in the history of the fishing industry of Monterey Bay was taken for canning purposes. The correlation between the water and the albacore fishery was very striking. The albacore arrived with and disappeared simultaneously with this water. This phenomenon strongly suggests that the pronounced irregularities of several fisheries along the California coast are intimately related to hydrographical changes, although unfortunately the data available do not allow us to be positive on this point.

As emphasized in previous reports, the hydrographical picture of Monterey Bay has proven to be decidedly complex. Not only do great changes take place throughout the year but very pronounced changes of a longer range also occur. In order to reach an understanding of this pronounced variability, it undoubtedly is necessary for us to extend our observations further out into the ocean. However, such an extension undoubtedly will not be sufficient. Close cooperation among the various scientific stations of our coast will be needed before a definite progress can be made toward the solution of these problems.

Hopkins Marine Station,
Stanford University,
Pacific Grove, California

REPORT ON OCEANOGRAPHY IN BRITISH COLUMBIA FOR THE YEAR 1932

C. McLean Fraser

Oceanography in British Columbia in 1932

As appropriations for oceanographic work in British Columbia were reduced in 1932 as compared with the immediately preceding years, there was little opportunity to launch out in new projects. Fortunately though, there was not any necessity to drop entirely any of the important problems that have been in progress for a period of years.

THE BIOLOGICAL STATION AT NANAIMO

In the work centered at Nanaimo progress was made in the oceanographic investigation of the Strait of Georgia. From the data previously obtained, it was considered advisable to make extensive collections of water-samples three times in the year, namely, in the spring, in the early summer (when the effect of the fresh-water of the Fraser and other large rivers is the greatest), and in the fall. These samples are examined for nitrates, etc., as formerly. The concurrent quantitative examination of the phytoplankton by making counts of the planktonts in a liter of sea-water, provides a basis for correlation.

As the nitrates and phosphates in the water of the strait are so high, new methods of determination have been evolved. Other improvements have been made in methods and in apparatus.

The life-history studies of some of the copepods found in the plankton were continued.

Water-temperature records covering a period of over 17 years in Departure Bay and over 12 years in the Strait of Fuca are being analyzed to study the variation trend.

The investigation of fiords is being continued. Jervis and Toba inlets have been added to the three fiords already under investigation. The work has not been entirely confined to these five inlets, but these have received more continued attention.

Food value of marine species

Much work is in progress on the food value of fishes and other marine species.

Salmon--Analyses of canned salmon--sockeye and pink--have been made from the early, medium, and late periods of the run in the sea and of the river-run, for protein, oil, and ash to determine calorific values.

Ling cod--The flesh and the skin of the ling cod have been similarly analyzed.

Pilchard--A comparison has been made of the calorific values in pilchards from the early and the late runs.

Oysters--A preliminary study of the three species of Ostrea cultivated in British Columbia waters, as to glycogen-content, has been made, as related to "fattening" and spawning.

Other physical-chemical investigations

An investigation has been made on different strength of pickle, on exosmosis and inward diffusion, when herring are salted in the round.

A preliminary survey has been made of the results of investigations on fish-net preservatives to serve as a basis for work on this problem.

Biological problems

Life-history studies

Salmon--Work on propagation and transplantation of sockeye and pink salmon. Hybridization and distribution of all species. No tagging has been done during the year but returns from previous tagging are still coming in.

Pilchard--Statistical analyses of the catch; anatomical studies show relationships; effect of pilchard effluent from fertilizer and oil plants.

Herring--Statistical analysis; length and age-composition of catches; population studies; various racial differences.

Ling cod--Spawning; early life-history; distribution; food.

Oysters--Study of the three species in spawning, setting, hybridization; experimental plantings.

Crabs--Rate of growth; mating; moulting; early life-history.

Razor clams--Spawning.

Bankia--A marine wood-borer; breeding season; temperature- and salinity-records to correlate with breeding season.

Faunistic studies

Faunistic studies are in progress on Protozoa, Polychaeta, Amphipoda, Mollusca, Fish.

A general faunal and floral check-list has just been completed.

Other biological problems

Parasites of fish--Studies are in progress of the Trematode, Cestode, and Nematode parasites of the marine fishes.

Food of sea fowl--Studied by examination of stomach-contents.

Food of fur seal--Stomachs of fur seals taken during their northern migration have been obtained and their contents examined.

FISHERIES EXPERIMENTAL STATION AT PRINCE RUPERT

Vitamin assays--Pilchard oil, halibut-liver oil, dogfish-liver oil, and shark-liver oil have been assayed for vitamins A and D. Oil-blending to get suitable proportions of these two vitamins has been attempted with considerable success.

Fish-oils--Much has been done on oxidation and hydrogenation of fish-oils. The unsaturated oils may now be made available for frying and shortening and in the manufacture of paints, varnishes, water-proof fabrics, and japans.

Freezing and cold storage--Modification of new methods in freezing and cold storage have been made so that they can be applied to plants already in use. Improvements have been worked out for railway transport. Biochemistry and biophysics of freezing have been studied.

Fish spoilage--Examination of the relation between protein decomposition and oil hydrolysis has been made in order to make use of the degree of oil hydrolysis as an index of "freshness."

Nutritive value of canned salmon--Biological assays have been made of sockeye and pink salmon, canned under various different conditions, with special reference to vitamins A and D.

Numerous papers have been published from both Nanaimo and Prince Rupert, mainly in "Progress-reports," "Bulletins," and "contributions."

Hydrographic survey

The Hydrographic Survey has continued the work of surveying and making soundings along different parts of the coast. A series of soundings, using the fathometer, in Jervis Inlet, fitted in well with the oceanographic work on fiords.

Meteorological Office

The marine thermographs-records and other physical data are sent in to the Office, as previously, from steamships plying between British Columbia ports and Australia, New Zealand, Japan, China, and the Philippines. No work in correlation of these data was possible during the past year.

Note--The report of the work from the station at Nanaimo is based on a report by the Director, Dr. W. A. Clemens; and that from Prince Rupert on a report by the Director, Mr. D. B. Finn.

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THE INVESTIGATIONS OF THE INTERNATIONAL PASSAMAQUODDY FISHERIES COMMISSION IN 1931 AND 1932

Charles J. Fish

For the past two years the scientific staff of the International Passamaquoddy Fisheries Commission has been carrying on extensive investigations to determine as accurately as possible the effect of the proposed tidal-power dams on the fisheries of Passamaquoddy Bay and adjacent regions in the Bay of Fundy and Gulf of Maine.

Field-work began in July 1931 and continued until October 1932. The personnel consisted of Dr. E. E. Watson, hydrographer; Dr. H. H. Gran, phytoplanktonologist; Mr. M. Graham, ichthyologist; Dr. C. J. Fish, zooplanktonologist and executive secretary; Mr. T. Braarud, assistant phytoplanktonologist; Dr. M. W. Johnson, assistant zooplanktonologist; Mr. C. J. A. Hughes, laboratory assistant; Mr. J. Bates, field assistant, and Miss H. E. Rigby, clerk.

Three vessels were utilized, the Prince and the Pelican, assigned by the Canadian and American governments, respectively, and the Nova IV, chartered during the period from December 1, 1931 until June 30, 1932. Assistance was also received from other vessels at intervals during the progress of the work.

Physical hydrography--The hydrographic program covered the region of the proposed tidal-power dams, the Bay of Fundy, and the eastern part of the Gulf of Maine. An intensive study was made of the passages directly affected by the proposed dams.

The object of these investigations was to ascertain the general movements of the water-masses under consideration, to seek the rapidity and source of water-renewal in the area, and to determine if possible what effect the dams might have on the whole Quoddy mixing mechanism.

Plankton--Phytoplankton and zooplankton investigations were made for the most part on common cruises covering eight lines of permanent stations in the Bay of Fundy and extending seaward from neritic waters along the coast of Maine as far west as Casco Bay.

Special stations were made for phytoplankton in spring in the Bay of Fundy and in the region of Cape Sable, Nova Scotia. Additional studies were made in Passamaquoddy Bay and in the entering passages. All studies on the relative production of diatoms were accompanied by hydrographic sections and analyses for nutrient salts in solution. Correlations were also made with solar radiation and turbidity of the water.

Special zooplankton stations, including hydrographical data, covered areas from Cape Sable to Halifax, Georges Bank to the Gulf Stream, and a series of stations in bays along the coasts of Maine, New Brunswick, and Nova Scotia. The latter observations were made with the object of determining the nature of the neritic communities and the possible biological contributions to offshore waters.

Seasonal observations were made in Passamaquoddy Bay and in the Bay of Fundy with supplementary surveys to determine the extent of zooplankton-contribution from Passamaquoddy Bay to the outside waters. In all 32 zooplankton cruises were made between July 28, 1931 and September 26, 1932.

In view of the importance of zooplankton as herring food, the investigations were extended over a wide area in order to determine the extent and location of production centers and the horizontal drift from productive waters. As a supplement to the study of the distribution of larval and post-larval stages in determining drift, a series of 446 drift-bottles was released in the Gulf of Maine and the Bay of Fundy. Twenty-four per cent of these have been recovered to date.

Ichthyology--Field-work in ichthyology consisted of a study of the production and distribution of herring larvae supplemented by a statistical study of herring catches made in weirs in the Quoddy Region. Collections of pelagic young stages were made from December to July 1932, throughout the Bay of Fundy, Cape Sable to Halifax, and to a lesser degree in the Gulf of Maine.

In connection with the herring studies 46 drift-bottles were released in a section off Yarmouth, Nova Scotia, of which but two have been recovered.

With the exception of Dr. H. H. Gran and Mr. Michael Graham who have returned to Europe, the scientific staff is now located in the laboratories of the Woods Hole Oceanographic Institution at Woods Hole, Massachusetts.

The results of the investigations are being arranged in a report to be submitted to the Commission prior to the termination of the work on June 30, 1933. Scientific reports by the individual members of the staff will be prepared for publication later.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

THE DEVELOPMENT OF OUR CONCEPTION OF THE GULF STREAM SYSTEM

C. O'D. Iselin

To any student of the physical oceanography of the North Atlantic Ocean, the current-system, popularly known as the Gulf Stream, is a problem in more ways than one. Not least among the difficulties is the confusion in the literature over the definition of the four chief names under which this current-system or parts of it are now known, namely, Florida Current, Gulf Stream, North Atlantic Drift, and Atlantic Current.

It might seem at first glance that the question of terminology was an unimportant one, but anyone reading back through the many papers that have been written about this mighty current will soon see that part of the misunderstanding is due to the fact that the term Gulf Stream means one thing to one writer and another to another. The various names by which the parts of this current are known have been used loosely largely for the reason that so little was known about the structure of its different sectors and about the forces acting to move the water along its great length. But we have now come to the time, mainly because of the sections made during the past two years by the Atlantis, when we have found out something about the structural changes the current undergoes between the Straits of Florida and mid-ocean. And for the eastern half of the ocean, we can turn to Helland-Hansen and Nansen for an authoritative summary of what is known about the complicated branching of the Gulf Stream, wisely called by them the Atlantic Current. Even though we are still far from understanding the forces which act to keep the water moving, it is clear from the Atlantis sections that on the basis of structure the stream naturally divides itself into three parts, and for this reason it would seem that the time has come to adopt a uniform and clearly defined terminology. Fortunately, there is no need to introduce new terms. It is mainly a question of defining more exactly those now in use among oceanographers and to hope that the same usage will be gradually adopted in all languages.

There is no question but that the term Gulf Stream among English-speaking people (and largely also in other languages) is popularly used for the whole current, under the impression that there is a warm river of water flowing out of the Gulf of Mexico, up along the eastern coast of the United States towards the "tail" of the Grand Banks, and thence to Europe and the Arctic. Historically also the name holds the lead in the literature of the last century. Thus in science the term should be continued and, as we shall see, the only safeguard necessary to avoid confusion is to speak of the "Gulf Stream system" as meaning the whole of the current, including the branches.

The controversy over the Gulf Stream has waxed and waned ever since the printing of Lieutenant Maury's wind and thermal charts in 1852. In 1870 a sort of crisis was reached with the publication of Petermann's paper, and his vigorous denial of the more moderate views of the leading English and American scientific men brings out clearly the two main conceptions of the Gulf Stream's influence in the eastern North Atlantic. Since by this time surface-salinity determinations had been made and a number of deep temperature-stations occupied, 1870 can be taken as the beginning of the modern scientific investigation of the Gulf Stream.

Until this time, the current had been purely a map-maker's problem. How far be-

yond the Grand Banks should the arrows be continued which show the strong flow out of the Gulf of Mexico? Rennell in 1832 had drawn them as far as the Azores and this was considered rather an extreme view. But with the increasing interest in meteorology and arctic exploration, scientific men soon came to see that the climate of northern Europe, and indeed also of such places as Iceland and Spitzbergen, was much milder than the average for similar latitudes. Sea-surface temperatures also showed relatively warm water extending much further north in the eastern Atlantic than elsewhere.

Then came Petermann and his able explanation of the whole situation. He claimed that a branch of the Gulf Stream flowed northward through the Norwegian Sea and even into the Arctic Ocean. With German thoroughness he supported his views by collecting all available surface-temperatures and constructing two thermal charts, one for July and the other for January. In his zeal to put forward a completely new theory he perhaps went too far, for he showed the Gulf Stream continuing as far as 82° north latitude and consisting in the arctic of all the water warmer than 2° at the surface.

Those opposed to these views (Findlay, Carpenter, and others) argued that the Florida Current did not have sufficient volume to extend to Europe and brought forward the prevailing southwest wind to explain the relatively warm water off Ireland and in the Norwegian Sea. Petermann replied that the wind was not always from the southwest and pointed out the relative warmth of the sea in winter, the great distance the wind had to move the water, and, more important, that the warmer water often remained in well-defined bands.

If Petermann had not called his northern relatively warm currents the Gulf Stream, his ideas would have had even more influence than they did, for he presented a very strong case. As it was, his opponents could always point to the immense distance between Florida and Norway and to the narrowness and shallowness of the Straits of Florida. It seemed preposterous, as indeed we now know, to think that all the warmest surface-water in the northeastern Atlantic had passed through the Straits of Florida.

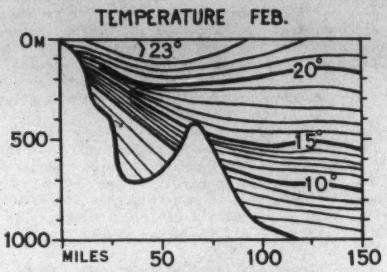
Here we see the main pitfall that has beset many meteorologists and students of oceanic circulation, who have used the term Gulf Stream when writing of the warm waters found off the coast of Europe. The tendency has been to convey the impression that the Gulf Stream is the chief source of warm water and the main means by which heat is transported northward.

In 1901 Dickson published another notable series of charts showing the monthly surface-temperatures in the North Atlantic. By this time the increasing information about the ocean had all tended to reduce the relative importance of a river-like Gulf Stream and to bring forward the wind as an agent for transporting warm water towards the shores of Europe. Dickson's paper perhaps represents the furthest possible advance in studying the course of a great current-system by means of surface-temperatures alone. Similar work since his time has produced little that is conclusive so far as pointing to the path of the various branches of the Gulf Stream system for the reason that the currents are deep phenomena and often hidden by the wind-controlled surface-movements.

As an example of recent work based on surface (in this case 0-100 meters) temperature and salinity conditions, I might mention the papers of LeDanois which have appeared frequently since 1923. Starting with the periodic appearance of relatively warm saline water in the Bay of Biscay, he has developed his "transgression" theory which, as we shall see, is a good exposition of what actually happens, but he has received little attention partly because he has stuck to the term Gulf Stream to describe the variable extensions of tropical water in the eastern Atlantic.

The immense influence on scientific and popular opinion of the many atlases of the North Atlantic which have appeared in the last 50 years should not be overlooked. They all give the impression that the Gulf Stream along the American coast is at least twice too wide and that it increases in width until by mid-ocean the current-lines often have spread out fanwise to a width of 600 miles or more. The whole of this familiar system of stream-lines or arrows has usually gone under the name of Gulf Stream.

This brings us to our first fundamental distinction. The word current in oceanography should, in my opinion, be reserved for the more powerful and permanent move-



THE FLORIDA CURRENT
AFTER WÜST

Fig. 1

ments which extend deeper than the drift set up by variable winds. Moreover, the word should include the whole depth of the moving water and not just the surface aspect of it. Thus a steady wind, for example, the trades, can set up a current, but the cyclonic type of winds found east of the Grand Banks, although prevailingly from the western quadrant, set up only a drift in that the movement must be shallow and varying in direction.

With this in mind we can see that atlases and so-called "current-charts" usually show the sum of the permanent currents and the prevailing drift. In the eastern North Atlantic, especially, there are both types of movement tending to bring relatively warm water northward, but the name Gulf Stream should only be applied to the deeper continuous lines of current. In fact, even this use is misleading and most authors now prefer to use the terms North Atlantic Drift and (North) Atlantic Current for the two types of movement found in this region.

We can see now what it was that Petermann from surface-observations thought to be a continuation of the Gulf Stream. The North Atlantic Drift, being as widespread as the wind, causes a general slow movement at the surface, but wherever a north-flowing branch of the Atlantic Current carries some of this surface-water northward, especially if the wind is not strong, the warmest water will be found at the surface in definite bands.

The branch of the Atlantic Current which enters the Norwegian Sea is known as the Norwegian Atlantic Current. Other branches have also been named, but their course is not so well known, being more or less masked by the North Atlantic Drift, so that only through subsurface observations can the intricate system of currents in the eastern North Atlantic be disclosed.

Since the name Atlantic Current is well established (Nansen, Helland-Hansen, and others) among oceanographers and nicely avoids the connotation of heat forever associated in the term Gulf Stream, its use should be continued and among our problems there remains the question of where the Gulf Stream stops and the Atlantic Current begins, for the latter is the continuation of the former. But before going into this point let us turn our attention briefly to the Gulf Stream proper.

Between Cape Hatteras and Nova Scotia we now have eight Atlantic sections and two others from other modern expeditions. These all show a sharp transition-zone between the relatively warm and motionless water-layers of the Sargasso Sea and the colder band of Slope-water which bathes the American continental slope. The latter averages about a hundred miles wide, while the transition zone is usually not more than 65 miles wide. The current is, of course, situated between the Slope-water and the Sargasso water and across its width the isotherms drop on an average of 600 meters. As revealed

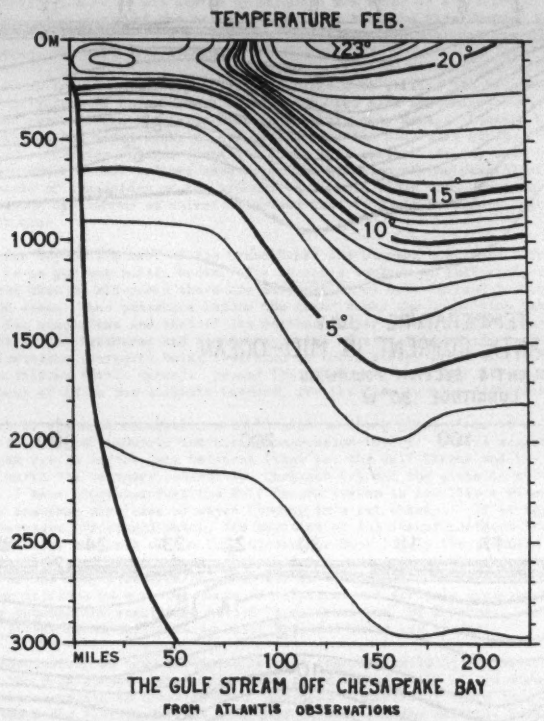
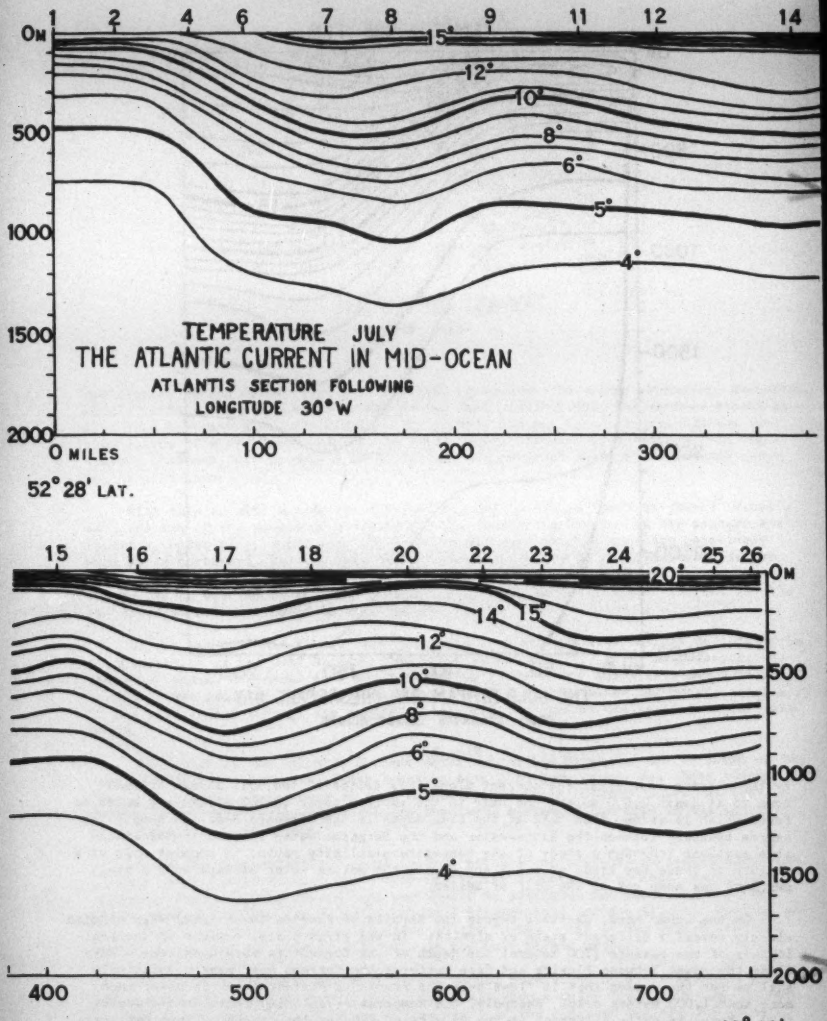


Fig. 2

by the sloping isotherms, the current along this sector of the Gulf Stream extends down to at least 2,000 meters and only in the surface layer (0-100 m) can any water be found which is warmer than that at the same depth in the Sargasso Sea. In short, the narrow boundary between the Slope-water and the Sargasso water is seen in the available sections (through a study of the temperature-salinity ratio) to consist only of a mixture of these two kinds of water, and of all the moving water perhaps only a small per cent has come out of the Gulf of Mexico.

On the other hand, sections across the Straits of Florida (Wüst 1924) when studied closely reveal a different state of affairs. In the first place, because of the shallowness of the passage (700 meters) the depth of the Current is very much less. Even along the coast between Florida and Cape Hatteras the Current must remain relatively shallow for the reason that it flows over the Pourtales Plateau which is never much more than 1,000 meters deep. Secondly, the temperature-salinity ratio at mid-depths (500 meters) is quite different in the Straits of Florida than north of Cape Hatteras. Although the study now being made of this problem is not concluded and the Atlantis is only now making the necessary observations, I do not hesitate to say that little water which flows out of the Gulf of Mexico remains in the Current by the time Cape Hatteras


1 2 4 6 7 8 9 11 12 14
0M
500
1000
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2000
15°
12°
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TEMPERATURE JULY
THE ATLANTIC CURRENT IN MID-OCEAN
ATLANTIS SECTION FOLLOWING
LONGITUDE 30°W
0 MILES
100
200
300
52° 28' LAT.
15 16 17 18 20 22 23 24 25 26
0M
500
1000
1500
2000
20°
14°
15°
12°
10°
8°
6°
5°
4°
400
500
600
700
LAT. 40° 02'

Fig. 3

is reached. The Current is of course continuous, but gradually the Gulf of Mexico water becomes replaced at all depths by Sargasso Sea water or a mixture of this and Slope-water. The secret of the matter probably is that the flow through the Straits of Florida has nothing to do with the more fundamental convectional current north of Cape Hatteras, the real Gulf Stream.

For these and other reasons it seems desirable to utilize the term Florida Current, not only for the flow through the straits, but also northward to the point where the Current runs off the Pourtales Plateau and into deep water. Between this point and the tail of the Grand Banks we can clearly use the name Gulf Stream, because the deep compact character remains unchanged along this sector. We may note here that Krummel and other German writers have urged the adoption of the name Florida Current for the whole of the stream on the grounds that it is older than the term Gulf Stream, but the latter has become so universally used that it would be almost impossible to discard it now.

How far beyond the tail of the Grand Banks the Current continues before it branches is as yet not surely known. The Atlantis section of 1929 along longitude 30° W shows that by mid-ocean there are at least three well-defined branches, each narrow and deep. Thus somewhere beyond the Grand Banks the transition between the Sargasso Sea conditions and that of the northern water ceases to take place in one sharp lift of the isotherms and becomes a series of step-like rises, each band of sloping isotherms (current) being separated by broad strips with relatively horizontal conditions (still water). Beyond the point where the Gulf Stream branches we should speak of it as the Atlantic Current, for the flow is of a different character.

There is one more conception which I wish to bring forward and it will take us again to the work of LeDanois and his transgression-theory. I have suggested that the Gulf Stream system beyond Cape Hatteras (that is, the Gulf Stream and the Atlantic Current) marks the boundary between the Sargasso Sea and the slope or northern waters. Moreover, I have suggested that the Gulf Stream system is not like a river consisting always of the same particles of water flowing in a set channel. If at any time there is more Sargasso (tropical) water, the position of the atrupt northern boundary will change, that is, the path of the Gulf Stream, or more likely the Atlantic Current, will be shifted northward. These slight lateral movements of the currents and especially of the eddy-like terminal branches of the Atlantic Current can often cause warm water to flood in over the banks and shallow seas formerly occupied by northern water and produce the conditions called "transgressions" by LeDanois. Ordinarily, the Gulf Stream marks the limit to which tropical water can spread.

In conclusion, we have attempted to show that logically it is justifiable to split up the Gulf Stream system into three parts on the basis of the structure of the current when examined in cross-section, and that historically there is good precedent to call these the Florida Current, the Gulf Stream, and the Atlantic Current. The latter is branched and the course of all of its branches have not yet been worked out, as the flow is masked by the shallow North Atlantic Drift.

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SUBMARINE MOCK-VALLEYS

W. M. Davis

Those peculiar features found in the sea-floors of continental margins and generally known as "submarine valleys" have been confidently interpreted by a number of geologists as the produot of stream erosion during a recent emergence of the continental slope, not yet obliterated during its more recent submergence. (A variant of this interpretation recently proposed by Shepard is to the effect that the valleys were eroded during a more ancient epoch of emergence, then filled and obliterated by marine sediments during a sufficiently long period of submergence, and lately revealed by the downsliding of the sedimentary filling to greater depths. See F. P. Shepard, Landslide modification of submarine valleys, Trans. Amer. Geophys. Union, 226-230, 1932. The same author has given an excellent summary of various other theories on this subject in

an article entitled "Submarine valleys," Geog. Rev., v. 23, 77-89, 1933.) It is not intended to imply by what here follows that the formation of submarine valleys by this method is either impossible or non-operative, but it is desired to point out certain difficulties in the way of its general acceptance. It is desired also to urge the maintenance of an open mind on the problem, inasmuch as certain collateral but essential consequences of the method, namely, the contemporary changes on the adjacent area of the land, have not yet been verified; indeed, not yet even considered in the writings of some of its most ardent advocates, such as Spencer and Hull, nor have alternative methods been given the hospitable and thorough consideration which Chamberlin has so well shown to be necessary in impartial and decisive investigation.

Certain examples of Californian submarine valleys are, I believe, beyond production by subaerial stream-erosion. They are shown on Davidson's chart (George Davidson, The submerged valleys of the coast of California, Proc. Calif. Acad. Sci., Geology, v. 1, 73-103, 1897) of the coast off the Santa Monica Mountains which trend east-west not far west of Los Angeles, and which I have recently studied in another connection as will be told in a forthcoming article entitled "The glacial epochs of the Santa Monica Mountains" in the Bulletin of the Geological Society of America for 1933. It will be there shown that the mountain streams eroded valleys of moderate depth below present sea-level and for a moderate distance seaward from the present shore-line, while the ocean was lowered perhaps 50 fathoms during the last Glacial Epoch of the Glacial Period, but that the valleys were smoothly filled and obliterated during and since the Post-Glacial rise of the ocean to its actual level. Yet several much longer and deeper submarine valleys are found in the same district, for the excavation of which no sufficient emergence is indicated by the land-geology since the land and sea assumed their existing areal relations in this region. It is therefore illogical to insist on such emergence, because it is based on the tacit postulate that submarine valleys can have originated only in one way. Moreover, at least the heads of these deeper valleys should have been much aggraded during and since the lower stand of the ocean in the last Glacial Epoch while the adjacent shallower part of the sea-floor was being built up with terrigenous sediments, had there not been some submarine agency in operation by which they were kept open. Hence, inasmuch as their valley-like form cannot be reasonably accounted for by their having had a valley-like origin, I propose to call them "mock-valleys."

The presence of fine sediments on the mock-valley floors has been appealed to by some observers as proving that they are not swept by a submarine current; but I question whether the occurrence of such sediments logically leads to any such conclusion. Just as the presence of muddy deposits in a low-water stream-bed does not in the least disprove the great erosional power of the same stream when it is in flood; and just as the presence of a seashore beach in calm weather does not disprove the power of the surf to shift the beach detritus and rasp the rock-floor beneath it during a severe storm; so the presence of fine sediments in a submarine mock-valley during fine weather when soundings are made does not disprove the power of storm-driven bottom-currents to shift such sediments and thus to modify the form of the mock-valley. In all three cases, the fine-weather deposits that are removed during a storm will be replaced by similar sediments when the storm subsides.

The localization of valley-maintaining currents along relatively narrow courses appears to be, in at least some rather striking examples, a consequence of shore-configuration. Thus the Vincente or Redondo submarine valley, some 15 miles southeast of the Santa Monica coast, may well be a consequence of a submarine current which branches at time of storms from the southeastward surface-currents in consequence of the westward advance of the San Pedro promontory a little farther south; and it is noteworthy that dredgings in this trough made by Ritter about 30 years ago led him to the belief that inshore detritus is swept through it in large quantities by an outgoing current (W. E. Ritter, A summer's dredging on the coast of California, Science, v. 15, 55-65, 1902). Moreover, Tangier Smith, citing Ritter, concluded that "the majority of submarine channels of California have been formed, or are at least kept open, by some cause now in operation" (W. S. Tangier Smith, The submarine valleys of the California coast, Science, v. 15, 670-672, 1902). This aspect of the problem needs to be pursued by new observation.

The greatest of the Californian submarine mock-valleys is that which heads in Monterey Bay, 70 miles south of the Golden Gate. A short, inner part of its length

was, in lack of control by soundings, inaccurately shown on Davidson's Plate IX. An assumed length of about 70 miles with outermost depth of about 1,700 fathoms is given to it by an adventurous series of extremely regular submarine, 100-meter contours, for which no adequate control by soundings was then provided, on the San Francisco Bay sheet of the 1:1,000,000 map of North America, published by the United States Geological Survey in 1914. An apparently more accurate indication of this great mock-valley is given on a chart of the southern California coast based on echo-soundings made by the United States cruisers Hull and Corry in 1923 and issued by the United States Hydrographic Office; the contours are here drawn with 100-fathom intervals down to 2,000 fathoms, but the spacing of the soundings a mile apart on lines square to the coast 10 miles apart does not suffice to guide the contours closely. More convenient than the general chart of the coast is an edition of Coast Survey chart 5402 for Monterey Bay, on which the Hydrographic Office has over-printed these echo-soundings and their contour-lines. But by far the best representation of this important area is given by many accurately located soundings taken in 1932 by the Coast and Geodetic Survey and shown with well-guided contours for 100-fathom intervals on a chart not yet published, with a blue-print of which I have been generously provided by the Director of that Bureau. It includes only the outer 50 miles of the great mock-valley, the inner part having been earlier surveyed with sufficient accuracy.

If the actual form of a submarine valley should be known in order to infer its origin, none of the earlier charts gives a sufficient basis for the discussion of this one. Its depth is so enormous that its explanation by stream erosion during a period of emergence must be ruled out as geologically inadmissible. The absence of large, tumultuous mounds at its lower end appears to exclude its production by landslides, whether such slides merely remove the filling of a stream-eroded valley or initiate an altogether new excavation. The provisional hypothesis as to its method of formation which seems most reasonable is in brief as follows:

Monterey Bay is not a "drowned valley"; it is the as yet unfilled part of a crustal depression between two upheaved mountain masses on the north and south. As the upheaved masses had been reduced to moderate or low relief before they were upheaved (Robin Willis, Physiography of the California coast ranges, Bull. Geol. Soc. Amer., v. 36, 641-678, 1925), so the depressed area presumably had a similar form before it was depressed; but during the depression it may have been irregularly warped, broken, and displaced, very much as the upheaved ranges were. Since the upheaval of the adjoining coastal ranges they have been liberally dissected, and some of the outwashed detritus, along with much more that has been brought from other ranges farther inland by the Pajaro and Salinas rivers, has been swept into the adjoining depression, thus converting its landward part into a low plain and shoaling its seaward part; hence it is not to be expected that the sea-floor should still exhibit any close imitation of the form that it was given by depression alone. And truly enough the sigmoid pattern of the mock-valley, along which the submarine slopes of the bay join in a line of continuous descent from the middle of the bay-shore, does not resemble the pattern expectable from crustal warping and displacement; for such displacement would probably originate irregularly disposed ridges, slopes, and basins. The floor of the present bay must have been heavily built up with terrigenous detritus, and during its upbuilding the distribution of detritus must have been more or less influenced by movement of the sea-water, either in general drifts or in more localized currents. The sigmoid pattern of the mock-valley may thus represent the course of a temporary submarine current driven seaward while the surface-waters are driven landward by on-shore storms. It is possible that the shore-waters would at such times gather a load of sediments which would increase their specific gravity and thus aid them in descending into the cold waters of the depths.

This explanation is at present altogether hypothetical for the greater part of the long mock-valley; but it is almost demonstrably true for its innermost two or three miles, which are well shown as to form, depth, and deposits on the admirable Lithologic Map of the Bay, based on a Coast Survey chart by Galliher (E. W. Galliher, Sediments of Monterey Bay, California, Mining in Calif., 41-81, 1932). This short part of the 70-mile mock-valley is narrow, steep-sided, and well-defined, with a depth of less than 100 fathoms; and it is enclosed by a smooth sea-floor which slopes gradually from the shore to a depth of only 30 fathoms. It is inconceivable that such a feature could have been kept open without the aid of a storm-driven, outsweeping current during the last Glacial lowering and rising of sea-level. Even today, the shore-

drift of detritus ought to close it, unless, as Tangier Smith well said, it had been "formed, or at least kept open, by some cause now in operation"; and the most likely cause in this instance is evidently an offshore, sea-floor current, driven out by the shoreward drift of surface-water during severe on-shore storms. If accurate surveys could be made close inshore, its head might be found to be longer and deeper in stormy winter weather and shorter and shallower during the fair weather of summer. The fact that the shallow floor and the valley sides and bottom are all covered with "very fine sand," as determined by fair-weather dredging, does not militate in the least against the temporary action of such a localized current as is here inferred; for fine sediments might be swept away whenever a storm-driven bottom-current is at work, only to be replaced by similar sediments when the current comes to rest.

It is only by individual study of many submarine valleys in close connection with the geological history of their coast that their origin can be discovered, and when thus discovered it is highly probable that they will be found to have many diverse origins. This paper is offered as a small contribution to such individual study.

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A BORE-HOLE IN THE BAHAMAS

Richard M. Field and Harry Hammond Hess

During the summer of 1932 a boring was made on the Island of New Providence, the Bahamas. The boring was made possible through grants from the Royal Society of Great Britain, the National Research Council of the United States, and private subscriptions. The hole was drilled by the E. J. Longyear Exploration Company. Acknowledgment is given the Longyear Company for their economy in operations. Special acknowledgments are due to His Excellency Captain B. E. H. Clifford, Governor of the Bahamas, and to public officials at Nassau for cooperation, which included both intense scientific interest and material help. The sinking of the bore-hole is an integral part of the project called the International Expeditions to the West Indies, which has been sponsored by the Department of Geology at Princeton University, with the advice of the Committee of the American Geophysical Union on Geophysical and Geological Study of Oceanic Basins.

The purpose of the drill-hole was to collect data on the following problems: (1) The origin of certain types of limestones; (2) dolomitization; (3) the stratigraphy of the Bahamas; and (4) relation of the calcareous rocks to the deeply submerged valleys.

The hole was drilled near the south shore of New Providence Island, six miles from the nearest deep water, thus avoiding any talus-deposit which may have been built out from the edge of the reef. The hole reached a depth of 395 feet, with 200 feet of core recovered.

Oolitic limestone occurs only near the surface. Alternating beds of slightly cemented calcareous sand and very porous cavernous limestone were found until dolomite was reached at 160+ feet. Several caverns or unconsolidated sediments, 5 to 15 feet thick, were encountered. The porosity of the limestone, as determined under the direction of R. T. Chamberlin, varied from 55 per cent near the top to 4.7 per cent in the dolomitic rock at the bottom of the hole, the last 50 feet being relatively dense. Microfossils were found only in extremely limited and thin horizons. The microfossils were present only as molds, all the original material of the shells having been dissolved away. The total evidence as to porosity, fossils, and caverns strongly suggests that the ground-water level was once 300 to 350 feet lower than at present. A paper which will be published shortly (Proc. Amer. Soc. Civil Eng.) as to the ground-water problems in New Providence Island, including the rise and fall of the surface of the ground-water table with the tides, is also contributory evidence as to the Pleistocene level of the ground-water table.

Chemical analysis by A. H. Phillips shows that the limestone is 99 per cent $CaCO_3$ to 160+ feet. Above this depth the following impurities occur: 0-1.3 per cent magnesium carbonate, and not over 0.1 per cent for iron, alumina, and silica. At 160+

feet there is an abrupt change to dolomite, with no apparent evidence of a disconformity. In the case of Funafuti the change from limestone to dolomite took place at 640 feet, and within a zone of 5 feet.

The fossils from the core have been determined by H. A. Pilsbry, who considers that "the core penetrates the Pleistocene into Pliocene," but not into the Miocene.

Submerged cliffs on the margins of the drowned valleys suggest that the reef-material may be as much as 4,000 feet thick.

A full report on the results obtained from the drill-hole will be published by the Geological Society of America.

Princeton University,
Princeton, New Jersey

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AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

S E C T I O N O F V O L C A N O L O G Y

Washington, D. C.
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REPORTS AND PAPERS

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VOLCANIC EXPLOSIONS AND OVERTHRUSTS

Walter H. Bucher

The problem of Heart Mountain and associated thrust sheets--On the west side of the Bighorn Basin, in the vicinity of Cody, Park County, Wyoming, Paleozoic limestones lie as isolated thrust-masses on top of the truncated edges of Mesozoic and Early Tertiary strata (see Geologic map of Wyoming, 1:500,000, U. S. Geol. Survey, 1925). Dake (C. L. Dake, The Heart Mountain overthrust and associated structures in Park County, Wyoming, J. Geol., v. 26, 45-55, 1918) was the first to recognize their structural nature. To the five thrust-masses shown on his reconnaissance map Hewett (D. F. Hewett, The Heart Mountain overthrust, Wyoming, J. Geol., v. 28, 536-557, 1930) added a sixth one.

Three of the thrust-masses are small isolated remnants, lying far out in the Basin. The northernmost is Heart Mountain, one of the landmarks of the Bighorn Basin, in T. 54 N., R. 102 W. It consists of a wedge-shaped plate of Ordovician to Mississippian limestones thrust on Paleocene beds. The easternmost remnant is found on the McCullock Peaks (see Hewett reference above), 12 miles east-northeast of Cody, in T. 53 N., R. 99 W., where small shattered and more or less brecciated masses of Mississippian and Ordovician limestone overlie horizontal Wasatch beds. The third and southernmost of these outlying remnants appears on the east end of Carter Mountain in T. 51 N., R. 103 W.

Three larger thrust-masses lie along the mountain front, all three with volcanic breccias along their west sides. Two rise north and south of the South Fork of Shoshone River, forming limestone cliffs that tower above folded and faulted Mesozoic beds (T. 52 N., R. 104 W.). The last and northernmost is seen in the limestone-cliffs north of Pat O'Hara Mountain, which rise above little disturbed Triassic red beds (T. 55 N., R. 104 W.).

The distance from McCullock Peaks to the western edge of the limestone-plates on South Fork of Shoshone River measures over 28 miles. It is generally assumed that these separate thrust-masses represent remnants of a once continuous thrust-sheet, produced in the course of normal orogeny and since dismembered by the forces of erosion.

This assumption meets with serious difficulties.

(1) Crustal deformation in the relatively simple, broad mountain-uplifts to the north, east, and south (Beartooth Mountains, Bighorn Mountains, Owl Creek Mountains) has produced only local overthrusting to the extent of a very few miles at most. Overthrusting to a distance of at least 28 miles would seem to require a mountain-uplift of correspondingly larger proportions. But the area west of the Heart Mountain overthrust-sheets and east of Yellowstone Lake is not wide enough to conceal beneath its cover of volcanic rocks a mountain-mass of dimensions much greater than those of the Beartooth Mountains.

(2) The folds in the Early Tertiary and late Cretaceous rocks beneath Heart Mountain as well as the two large asymmetrical folds of Rattlesnake and Pat O'Hara Mountains and the folds farther south along the western border of the Bighorn Basin are steepened on the west side, that is, they indicate movement from the east toward the west (see Tectonic sketch-map of the Beartooth-Bighorn Region, by Walter H. Bucher in Walter H. Bucher, W. T. Thom, and R. T. Chamberlin, Geologic problems of the Beartooth-Bighorn Region, to appear in an early issue of the Bull. Geol. Soc. Amer.). The thrust-masses, on the other hand, which overrode these folds, moved from west to east. This is a most abnormal relation.

(3) The thrust-masses consist of the Paleozoic limestone-series, from the Ordovician Bighorn limestone to the Mississippian Madison and locally possibly even younger beds. Beneath these, the normal sequence of the region shows over 1,000 feet of Cambrian rocks, largely strongly micaceous shales (for recently measured sections, see R. V. Hughes, The geology of the Beartooth Mountain front in Park County, Wyoming, Proc. Nation. Acad. Sci., v. 19, 239-253, 1933). In the process of overthrusting, the limestone-series must have been sheared off the underlying Cambrian shales and carried beyond them for a distance of at least 28 miles.

(4) The west side of the overthrust limestone-sheets abuts against and is overlapped by the thick volcanic agglomerates which form such conspicuous cliffs in Shoshone valley. Below these farther west, lie bedded tuffs and later intrusive igneous masses. Nowhere is there any sign of the upthrust-center which must have acted as the plunger which is needed to push the limestone-sheets far out to the east.

A possible solution--The writer's cursory inspection of this region was made in the company of R. T. Chamberlin and W. T. Thom, Jr., which developing plans in connection with the cooperative Beartooth-Bighorn project (see abstract of the joint paper on Geologic problems of the Beartooth-Bighorn Region in the report on the 45th annual meeting of the Geological Society of America in Cambridge, Mass., Dec. 28-30, 1932). The difficulties in the way of an interpretation in terms of normal orogeny loomed large in the field. To the writer, an entirely different origin seemed indicated. This is here outlined in order to secure the criticism of the volcanologists and such suggestions as may be of value in connection with the detailed field-studies which are planned as part of the Beartooth-Bighorn project.

The writer thinks it possible that the limestone-plates which constitute the thrust-masses of this region were thrust eastward and scattered much as they exist today by the horizontal component of the force of a large volcanic explosion.

Throughout the Beartooth Mountains in the north, intrusive igneous rocks have tended to spread laterally within the thick Cambrian shales. It is thought that something like this occurred in a broad uplift which occupied the center of the volcanic area west of the thrust-sheets. The volcanic gases, perhaps largely pent-up steam, exploded in such a way as to shear off large sheets of limestone from the highly micaceous Cambrian shales and to drive them eastward (or, perhaps better, southeastward), down the pediment slope into the plain. Following the later extrusion of vast quantities of agglomerates and lavas, the central zone of volcanic activity was depressed in the form of a broad gentle syncline, carrying the underlying structural uplift out of sight.

Overthrusts on the borders of the Ries Basin--Such an interpretation is by no means without a parallel in geology. Thirty years ago (W. Branca, Das vulkanische Vorries, Abh. Akad. Wiss., Berlin, 1903) it became evident that a large volcanic explosion must have been responsible for the peculiar structural features of the Ries Basin in southern Germany. [For the chief literature see A. Bentz, Das Nördlinger Riesproblem und seine Deutungen, Sitzber. Preuss. Geol. Landesanstalt, Heft 3, 85-86, 1928. An exhaustive bibliography is given in R. Löffler, Beiträge zur Riesentstehungshypothese, Jahresber. u. Mitt. Oberrh. Geol. Ver., N.F., v. 14, pp. 75-83, 1925 (1926).]

The "Ries" is a nearly round topographic basin, measuring 21 to 24 km (13-15 miles) in diameter, the largest part of which lies concealed beneath upper Miocene lake-beds and later sediments (Zone der jungen Sedimentation in Fig. 1).

Where the underground lies exposed, it appears as a heterogeneous jumble of blocks with large and small fragments of crystalline rocks of the basement complex conspicuous among such of Triassic and Jurassic strata.

Recent measurements with the torsion-balance seem to indicate an explosion-funnel beneath these debris which is 12 km in diameter, 0.9 to 1.3 km deep, and has walls sloping 10° to 15° toward the center (A. Bentz and Karl Jung, Drehwaagemessungen im Ries bei Nördlingen, Zs. Geophysik, v. 7, 1-21, 1931).

The Basin is surrounded by a marginal zone, generally several miles wide, which consists of similar heterogeneous blocks of all the formations of the region from the crystalline rocks of the basement complex to the youngest rocks of the region, the upper Malm. Locally these blocks lie in the form of imbricated thrust-slices (Schollen- und Schuppenzone of Fig. 1).

Beyond this relatively narrow marginal zone lie the undisturbed Upper Jurassic strata on the Alb Plateau. But on top of them are found breccias and larger plates consisting of rock materials derived from lower horizons which have been thrust upon them. Along the inner edge of this zone the thrust-plane is exposed here and there

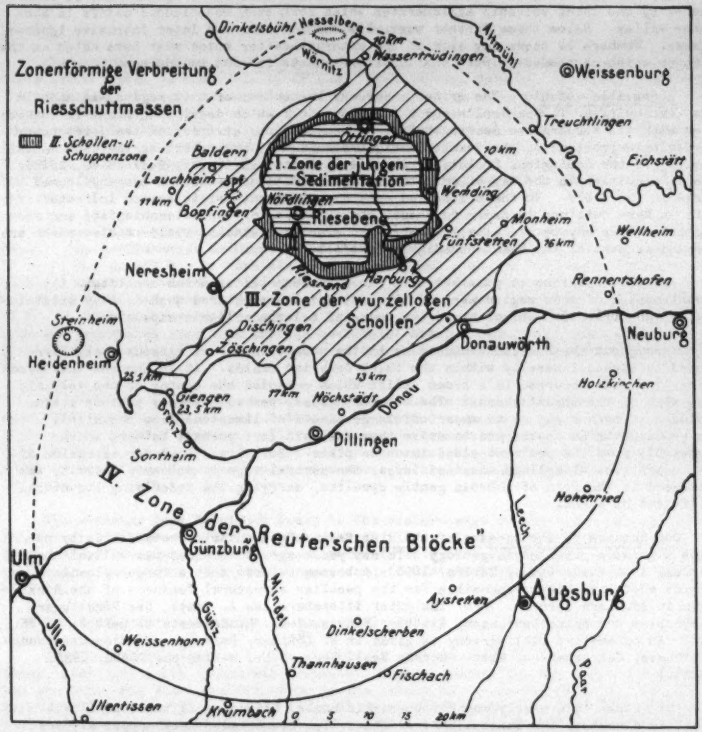

Fig. 1--Tectonic sketch-map showing the Ries Basin in southern Germany and the zonal distribution of materials thrust radially outward from it (Reproduced from Alfred Bentz, Geologische Beobachtungen am westlichen Riesrand, Zs. D. Geol. Ges., v. 79, Fig. 7, 426, 1927)

beneath a thrust-plate. At such places old gravels are found beneath the thrust-sheets which show the effects of the pressure exerted by the overriding thrust-mass.

Locally the foreign materials are found as far as 25.5 km (15.8 miles) from the topographic border of the Ries Basin, that is, some 22 miles from the center of the explosion! The zone within which such thrust-out, foreign materials occur (generally in the form of breccias), is shown by oblique shading in Figure 1 (Zone der wurzellosen Schollen). The thickness of the overthrust materials varies from a few centimeters to that of hills 70 meters high (230 feet).

Even beyond this wide zone isolated blocks of Upper Malm limestones are found widely distributed, especially south of the basin. On Figure 1 they are designated as "Reuter'sche Blöcke," after L. Reuter who first described them (L. Reuter, Die Verbreitung jurassischer Kalkblöcke aus dem Ries im Südbayerischen Diluvial-gebiet, Jahresber. u. Mitt. Oberrh. Geol. Ver., N.F., v. 14, 191-218, 1925 (1926)). Blocks

of diameters from 20 to 40 cm weighing 10 to 25 kg are found as much as 60 km (37 miles) from the edge of the Ries Basin, that is, up to 44 miles from the center of the explosion.

Following the explosion, acid tuffs were extruded for some time, apparently from local, small vents. These are generally unstratified and contain many fragments derived from the underlying sediments and especially from the crystalline rocks of the basement complex. The latter generally show evidence of partial fusion under peculiar conditions. Their physico-chemical study promises important information concerning the nature of the explosion. (See Wilhelm Ahrens, Die Tuffe des Nördlinger Rieses und ihre Bedeutung für das Gesamtproblem, Zs. D. Geol. Ges., v. 81, 94-99, 1929. Ahrens considers it possible, if not probable, that the Ries explosion resulted from the local melting of the crystalline rocks of the basement-complex through the action of superheated gases.) No lava was brought forth at all.

Comparisons--In view of the wealth of detailed field-studies that have been made, there can be no doubt about the reality and the magnitude of the Ries eruption. It is of special interest because the order of magnitude of the distances to which large slices of limestone-formations (with shales and sandstones) were moved and overthrust horizontally is the same as that postulated in the case of the Heart Mountain thrust-sheets. It differs from the volcanic eruptions of historical time in the horizontal displacements produced and in the intensity displayed.

Horizontal displacements occurred in an experiment which Kranz (W. Kranz, Das Nördlinger Riesproblem, II, Jahresber. u. Mitt. d. Oberrh. Geol. Ver., N.F., Bd. 2, 54-65, 1912) performed in order to reproduce the Ries explosion in a model on the scale of 1:15,000. Horizontal layers of sand, clay, and cement of appropriate thickness, forming a disc 3.25 meters in diameter, represented the formations of the region before the explosion. A charge of black powder, of computed quantity, was placed about 20 cm beneath the surface. The explosion cleared out a wide circular area in the layers representing the sedimentary cover, and produced a shallow inner explosion-funnel in the "crystalline basement." The remaining ring of "sediments" was cracked into many pieces which were shoved horizontally outward, locally as much as 30 cm, although the explosive lay about 10 cm below the base of the sediments. It is evident that much larger horizontal displacement could have been obtained in this experiment if the explosive had been placed inside a dome of sediments, well above the base of the arch.

Even so, the energy required to produce similar effects on the scale of the Ries Basin and, more so, on the scale of the Heart Mountain thrust-sheets, is truly stupendous. It would require explosive activity on a scale far greater than that of explosions of historical time.

Unmistakable evidence pointing to volcanic explosions far greater than those recorded by man exists at more than one place. The region which adjoins the Heart Mountain thrust-blocks on the west is one of these.

In the valley of the South Fork of Shoshone River, some 18 miles (29 km) southwest of the westernmost thrust-block of the Heart Mountain group, the "early basic breccia" reaches a thickness of 282 meters (925 feet), formed to all appearances in a single event (for this and the other measurements the writer is indebted to Dr. J. T. Rouse, whose detailed description of this region is awaiting publication). Huge angular blocks of andesites, rhyolites, and basalts abound in it. One large block is seen in cross-section in the cliffs on the west side of the valley, six miles southwest of the point of greatest thickness mentioned above, where the thickness of the lower basic breccia has dropped to about 150 meters (500 feet). The visible section of this block measures 53 by 15 meters (175 by 50 feet).

Compare with this the quantity and size of fragmental materials which resulted from the famous eruption of Krakatau in 1883. According to Verbeek, two-thirds of all material ejected by Krakatau fell within a circle of 15-km (9.3-mile) radius. In different parts of this circle the average thickness of the accumulated volcanic materials was found to range from 6 to 40 meters (19.6 to 130 feet); see R. D. M. Verbeek, "Krakatau," Batavia, p. 140, 1886. Near the center, single ejected blocks of pumice reached the volume of cubic meter, while blocks of volcanic glass reached half that volume.

What is perhaps the most remarkable record of explosive volcanic activity is found in the uninhabited mountains along the frontier between Tibet and India, southwest of the Tibetan Manasarowar lakes. Here large masses of light-colored Permo-Carboniferous and Triassic limestones and of other rocks lie as foreign masses on top of a synclinal belt of Upper Jurassic and Cretaceous shales ("Spiti shales" and "Flysch"). From the distance they have all the appearance of tectonic "Klippen" and were interpreted as such by Suess (in the third volume of the Antlitz der Erde, which was issued in 1901; see pp. 276 to 279 of v. 3 of the English edition by Sollas and Sollas where in Fig. 15, p. 278, a tectonic sketch-map of the region is given which shows the distribution of these "Klippen" in relation to the regional structure--after Diener). But more detailed mapping by A. von Krafft (A. von Krafft, Notes on the "exotic blocks" of Malla Johar in the Bhot Mahals of Kumaon, Mem. Geol. Surv. India, v. 32, pt. 3, 1902) showed that what had been called "Klippen" are only the largest of a vast number of sedimentary blocks which are part of a volcanic breccia of gigantic dimensions. His photographs show the striking contrast between the gentler slopes formed by the volcanic breccia and the cliffs of the "exotic blocks" which crown conspicuous mountain peaks. A. v. Krafft estimated that there must be many hundreds of blocks which exceed 10 feet in diameter, a few dozen having the dimensions of whole hillsides. Blocks of smaller dimensions are "quite innumerable."

The most remarkable feature of these "exotic blocks" is neither their size nor their number and variety (A. von Krafft lists the following horizons as represented among the "exotic blocks": Permo-Carboniferous; Lower Trias; Middle Trias (Muschelkalk); Upper Trias (L. and U. Carnic; Dachsteinkalk); Lower Lias; Upper Jurassic (Spiti shales, doubtful); Lower Cretaceous sandstone; Upper Cretaceous flysch, including the tuffs of its highest member), but their facies and faunistic character. Almost all horizons which could be identified by their fossils differed more or less definitely in their lithologic character from the facies which exist in the region. Three horizons also differ strikingly in their faunas, namely, the Permo-Carboniferous, Upper Carnic, and Liassic limestones. The conclusion seems inevitable that they can not have been derived from the immediate vicinity, but must have been brought to their present location from some distance, from the unexplored region to the north.

Their intimate association with the volcanic breccia proves that very large volcanic explosions were involved. v. Krafft thought that the matrix of the volcanic breccia was true lava and that the exotic blocks, after the eruption, were "floated" to their present location by the lava. He describes the loose debris of the region as consisting "of large and small blocks of green and red andesite and finer volcanic material mixed with a multitude of pieces of sedimentary rocks." He adds: "I was for some time in doubt as to whether this does not represent a volcanic agglomerate," but concludes: "I do not, however, now believe that true agglomerates are anywhere existent in Johar" (loc. cit., p. 137). But the highly altered character of much of the volcanic material, evident in the petrographic description, casts doubt on the conclusiveness of the evidence. Whether they were actually floated or not, they bear evidence of volcanic explosions which seem to exceed by far in violence those of historical times.

Conclusion--On the basis of the above considerations, the writer considers it possible that a large volcanic explosion moved the thrust-masses of the Heart Mountain region from an original position farther west to their present positions. The explosion would have blasted away the western portion of the limestone-plate, driving the easternmost portions outward, probably downward onto the erosion-slope of the plains below. The larger plates would have been moved only a relatively few miles. The outermost fragments would have become detached and propelled far beyond, their remnants forming Heart Mountain and McCullock peaks. This would incidentally explain the curious structure of Heart Mountain which consists of a wedge of limestone formations dipping northeastward so that the eastern part of the mountain is formed by Mississippian, the central part of Devonian, and the western part of Ordovician limestones, the horizontal base of the limestone-cap cutting diagonally across the formations. This would represent the plane of shearing along which the limestone-mass of the mountain tore from its original location.

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FURTHER REMARKS ON THE CRIPPLE CREEK VOLCANO, COLORADO

G. F. Loughlin

(Abstract)

Structural evidence, particularly in the deeper mine-workings, indicates that the volcano, which is of Tertiary age, was developed by explosive eruptions at a number of points along intersecting fissure-systems that had been formed in pre-Cambrian granite by east-west compression, probably during the Laramide revolution. The volcanic breccia, which consists principally of phonolitic material, appears to fill several elongate or elliptical funnel-shaped openings that coalesce upward and taper downward into roots. Local adjustments that followed the principal explosive eruptions developed fissure-systems in the breccia parallel and transverse to the older fissure-systems and permitted the intrusion of dikes and irregular masses of latite-phonolite and syenite within the breccia mass. Mild regional readjustment, caused by compression in a nearly north-south direction, ensued and reopened these fissure-systems within and around the breccia mass. It was followed by the relatively widespread intrusion of dikes and irregular masses of phonolite. Local readjustment then recurred repeatedly, mainly along the master fissure-systems, and was followed by three successive intrusions of alkaline basaltic dikes and finally by the formation of mineral veins.

A more detailed discussion will be included in a forthcoming paper to be published by the Colorado Scientific Society.

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SOME FEATURES OF THE VOLCANIC SEQUENCE IN THE CASCADE RANGE IN OREGON

Eugene Callaghan

The following is a condensed version of part of report on geology and ore-deposits of Cascade Range in Oregon in preparation; it is published by permission of the Director, United States Geological Survey.

In a certain sense the Cascade Range is the dissected western margin of the large area of dominantly volcanic rocks in the northwestern part of the United States. This is particularly true of the Range in California and in the southernmost part in Oregon, but farther north topographic features, distribution of rock types, and linear elements appear which distinguish the Cascade Range from adjacent provinces. It is the purpose of this paper to point out these elements and to show the distribution and stratigraphic arrangement of rock types, so far as our present knowledge permits, as well as some of their petrographic features.

For the purposes of geologic description it has been found convenient to divide the Cascade Range south of Mount Hood in two parts, the Western Cascades and the High Cascades (Fig. 1), on the basis of a pronounced unconformity in the stratigraphic sequence of lavas. This in turn accounts for the rolling upland character with partial or total preservation of volcanic surfaces on probably very late Tertiary and Quaternary rocks in the High Cascades as compared with the deeply dissected surface on an older volcanic series in the Western Cascades.

The older series is divided into two groups on the basis of the dominant rock-type and associated structural features. One of these is characterized by black lavas with associated red agglomerates, tuffs, and rhyolite; the other of irregular flows of dominantly andesitic lavas with rhyolite and abundant andesitic and rhyolitic pyroclastic rocks in most places. The black lavas occur in two separate areas along the western margin of the Range--one in southern Oregon in the Rogue River valley area and the other along the Willamette Valley. These flows are sufficiently extensive to reveal deformation-structure. In both areas they dip gently to the east or northeast, except in the area east and northeast of Salem where the dip is to the northwest. In southern Oregon they rest upon an arkosic formation of Eocene age, and the paleobotanical work of Chaney on intercalated sediments indicates that they range in age from

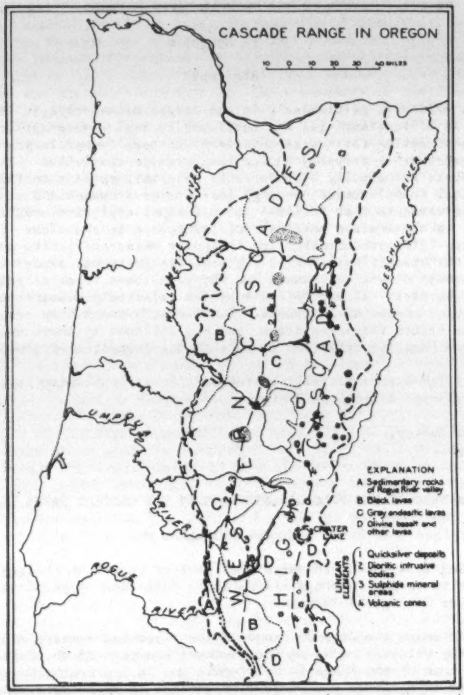

Fig. 1

Eocene to the middle Miocene. Along the Willamette Valley they rest upon Oligocene sediments.

The gray andesitic series occupies the remainder of the Western Cascades from the Rogue River north toward the Columbia. On account of the extreme heterogeneity of flows and pyroclastics, deformation-structures can not be readily ascertained, but both warping and faulting have been noted. In the vicinity of Rogue River these lavas appear to interfinger with the black lavas, and farther north they are stratigraphically higher, but no distinct unconformity has been noted. No definite fossil evidence has been found, but it is believed that these rocks are largely of Miocene age.

The younger series of volcanic rocks, which occupies the High Cascades and extends down valleys in the older series in long tongues, is characterized by olivine basalt, which is essentially a part of the great lava plateau, consisting largely of similar rocks extending far to the east and southeast. This series of flows contains interbedded red agglomerates near the summit of the Range, but in the long tongues extending to the west, flow rests upon flow without intervening material. The sources of these flows were probably in small cones, which have been covered by later deposits or obliterated by weathering and glaciation. No deformation-structures other than faults south of Crater Lake have been noted. The age of the olivine basalt is not definitely known. It was deeply trenched during the last period of glaciation, but

the lower limit of age is not known. Correlation with contiguous areas of similar rocks suggests that part of the series may be Pliocene.

Certain linear elements of the Range may be pointed out (Fig. 1). Attention has often been drawn to the elongate outline of the Range as a whole. A number of quicksilver deposits or prospects occur along the western margin of the Range, either in the older rocks or in the volcanic rocks. Farther east, a line of sulphide-mineral areas extends from near the California line to a point near the Columbia River. This line approximately coincides with a line of stocks, dikes, and plugs of porphyritic diorite and granodiorite. Still farther east, the elongate area of young lavas is surmounted by large and small volcanic cones of varying age and structure. Many of these cones antedate the last period of extensive glaciation and are deeply trenched or even largely obliterated. The flows from other cones and the great pumice blanket in the vicinity of Mt. Mazama (Crater Lake) lie upon glacial drift.

The lavas that form the base of the succession in most parts of the Western Cascades are characterized by their prevailing black appearance, and by their occurrence as flows that have great lateral extent as compared to their thickness, and therefore present a distinctly bedded appearance. In many respects they closely resemble the Columbia River basalt and are generally called basalts, though chemical and microscopic study indicates that probably few of the flows are true basalts. The analysis of one of these black lavas in column 3, Table 1, shows that the SiO_2 is high and the content of CaO and iron oxides approaches those in ordinary andesite. (It has been found necessary to distinguish between andesites and basalts on the basis of proportion of ferromagnesian to feldopathic constituents rather than the kind of plagioclase because of the relatively high CaO-content of the plagioclase and the large proportion of SiO_2.) Analyses of two black lavas of the Columbia Plateau are included in the same Table for comparison. Under the microscope this black lava shows phenocrysts of labradorite, augite, and magnetite together with very small grains of the same minerals in a brown glass base. It is the glass, and not a predominance of ferromagnesian constituents, that makes the rock black. Olivine crystals are not abundant, though pseudomorphs occur in a number of the flows examined.

The gray andesitic series, which lies north and east of the black lavas, is characterized by several kinds of effusive rock, ranging from basalt to rhyolite in composition. Pyroclastics are abundant and consist chiefly of gray or greenish-gray tuffs with fragments less than an inch in diameter. Probably the most abundant type is a gray andesite--very near basalt in composition--which occurs throughout the series but appears to be more abundant in the southern part. Three analyses (Table 1, columns 4-6) show that CaO is about equal to iron oxides which are less abundant than is usual in the true basalts. Consequently, the plagioclase is very calcic, but ferromagnesian minerals are much less abundant than in the true basalts. Most of these rocks are porphyritic with phenocrysts of labradorite, augite, and magnetite in a ground-mass of very fine grains of the same minerals. Another common type of flow is represented chemically in column 7, Table 1. It is marked by an increase of silica and the dominance of Na_2O over CaO, and is made up of phenocrysts of andesine or oligoclase, augite or hornblende, and magnetite in a very fine-grained ground-mass. The proportion of ferromagnesian minerals is very low and in most specimens they are represented by chlorite pseudomorphs. Rhyolites represented by column 8, Table 1, are the least abundant of the flow rocks in this series. Those specimens examined consist of oligoclase phenocrysts in a glassy or devitrified ground-mass. Quartz occurs as fine grains in spots or streaks in the flow banding. Ferromagnesian minerals are generally absent or represented by a few chlorite pseudomorphs in most specimens, though a few specimens containing hornblende were noted. Magnetite occurs as phenocrysts or as very fine grains, which in the red rhyolites are surrounded by red iron oxide. Basalts with an abundance of augite and a little olivine were found at the summits of several ridges, especially in the northern part of the Western Cascades.

The dioritic intrusive rocks are porphyritic in the sense that they grade from rocks with a dominance of felsitic ground-mass to those in which a dominance of phenocrysts gives them a granitoid appearance. The phenocrysts consist chiefly of calcic or sodic andesine, augite, and magnetite. Hypersthene occurs in some of the bodies as phenocrysts. The length of the plagioclase phenocrysts ranges from 1 to 4 mm, but ferromagnesian phenocrysts are smaller. The ground-mass consists of smaller grains of plagioclase, orthoclase, and quartz. Augite is commonly found partly or wholly changed

Table 1--Analyses and norms of typical rocks of Western Cascades and related rocks

Column	1	2	3	4	5	6	7	8	9	10
SiO_2	49.08	54.50	57.47	53.27	54.25	55.18	62.72	69.58	49.3	59.3
Al_2O_3	13.71	14.43	14.95	17.08	16.46	15.57	15.04	13.68	14.1	16.6
Fe_2O_3	1.25	2.17	2.05	2.93	3.08	3.20	1.73	1.39	3.4	3.1
FeO	13.02	8.80	7.18	6.06	5.92	6.06	4.44	1.88	9.9	3.5
MgO	4.58	4.24	2.74	5.12	4.46	4.15	2.19	0.63	6.4	3.4
CaO	8.44	8.01	6.63	9.60	8.79	7.60	3.83	2.68	9.7	6.3
Na_2O	3.17	3.05	3.45	2.28	3.46	3.08	4.18	3.66	2.9	3.6
K_2O	1.31	1.29	2.15	0.72	0.80	1.40	2.26	3.22	1.0	1.9
H_2O	0.90	1.09	0.55	1.52	1.32	2.03	1.91	1.46		1.3
H_2O-	0.20	0.29	0.45	0.15	0.26	0.40	0.34	0.45		
CO_2				0.08		0.07	0.38	1.38		
TiO_2	3.56	1.69	1.60	1.04	1.28	1.46	0.95	0.44	2.6	0.7
P_2O_5	0.73	0.21	0.32	0.20	0.23	0.14	0.21	0.09	0.5	0.2
MnO	0.25	0.10	0.12	0.15	0.13	0.14	0.10	0.07	0.2	0.1
	100.20	100.13	99.66	100.20	100.44	100.48	100.28	100.61		
				Norms*						
Q		7.02	10.32	8.82	6.12	9.42	17.28	32.82		
or	7.78	7.78	12.79	3.89	5.00	8.34	13.34	18.90		
ab	27.25	25.68	28.82	19.39	29.34	26.20	35.63	30.92		
an	18.90	21.68	19.18	34.47	26.97	24.46	15.29	3.61		
C								2.86		
wo	7.89	7.19	4.99	5.34	6.61	5.45				
en	8.80	10.60	6.90	12.80	11.20	10.30	5.50	1.60		
fs	13.33	11.75	8.98	7.26	6.47	6.20	5.28	1.72		
fo	1.89									
fa	3.06									
mt	1.86	3.25	3.02	4.18	4.41	4.64	2.55	2.09		
il	6.84	3.19	3.04	1.98	2.43	2.89	1.82	0.76		
ap	1.68	0.34	0.67	0.34	0.34	0.34	0.34	0.34		
cc							0.90	3.20		

References for numbered columns as to rock, place, and analyst

1. Basalt. The Dalles, Oregon. H. S. Washington, analyst (Washington).
2. Yakima basalt. Clalum Ridge, Washington. George Steiger, analyst (G. O. Smith).
3. Black labradorite andesite. McNeil Creek, Jackson County, Oregon. J. G. Fairchild, analyst.
4. Labradorite andesite. Near Grizzly Saddle, Bohemia District, Lane County, Oregon. George Steiger, analyst.
5. Labradorite andesite. Top of Gold Hill, Blue River District, Oregon. George Steiger, analyst.
6. Labradorite andesite. Bohemia Mountain,
7. Augite andesite. South Grouse Mountain,
8. Rhyolite. Vesuvius mine,

   } Bohemia District, Oregon. George Steiger, analyst.

9. Average plateau basalt (Daly, R. A., 1925).
10. Mean of 20 analyses of hypersthene and augite andesite (Osann-Rosenbusch, 1923).

*Norms in all three tables recalculated by Jewell J. Glass according to methods of Barth (Min. pet. Mitt., v. 42, 1-7, 1931) and Washington (Min. pet. Mitt., v. 43, 63-66, 1932).

Table 2--Analyses and norms of intrusive rocks in Western Cascades and a related rock in Washington

Column	1	2	3	4	5
SiO_2	52.67	61.99	65.16	65.71	64.04
Al_2O_3	17.36	15.69	15.24	14.29	15.58
Fe_2O_3	3.37	2.96	2.08	2.44	1.26
FeO	5.14	2.85	3.04	2.85	3.22
MgO	5.06	2.76	2.22	2.15	3.23
CaO	8.80	4.62	4.69	4.13	4.51
Na_2O	3.06	3.52	3.62	3.55	4.01
K_2O	0.73	1.60	2.08	2.42	2.22
H_2O	2.15	1.83	0.77	0.82	1.17
H_2O-	0.18	0.13	0.13	0.11	0.19
CO_2	0.09	0.75	0.17		
TiO_2	1.13	0.73	0.74	0.81	0.69
P_2O_5	0.29	0.31	0.29	0.20	0.16
MnO	0.17	0.06	0.09	0.18	Trace
	100.20	99.80	100.32	99.66	100.39
		Norms			
Q	6.72	23.76	23.16	23.94	17.34
or	3.89	9.45	12.23	14.46	12.79
ab	25.68	29.34	30.39	29.87	34.06
an	31.97	16.40	19.18	15.85	18.07
C		2.24			
wo	3.94		0.58	1.51	1.39
en	12.70	6.90	5.60	5.40	8.00
fs	5.15	1.58	2.77	2.24	3.56
mt	4.87	4.41	3.02	3.48	1.86
il	2.13	1.37	1.37	1.52	1.37
ap	0.67	0.67	0.67	0.34	0.34
cc	0.20	1.70	0.40		

1. Augite diorite. Small plug, Bohemia District, Oregon. T. Kamada, analyst.
2. Augite dacite porphyry. Small plug, Bohemia District, Oregon. R. B. Ellestad, analyst.
3. Augite-hypersthene granodiorite porphyry. Core of dike, Bohemia District, Oregon. T. Kamada, analyst.
4. Hornblende-augite granodiorite. Small stock, Bohemia District, Oregon. R. B. Ellestad, analyst.
5. Hornblende-biotite granodiorite. Snoqualmie batholith, Kittitas County, Washington. H. N. Stokes, analyst. (G. O. Smith).

to fibrous hornblende or to chlorite. Orthoclase partly replaces the plagioclase and much of the plagioclase is zoned and mottled, registering changes in the end-stage solutions. Analyses of representative types are shown in columns 1 to 4, Table 2, and an analysis of hornblende-biotite granodiorite from the Cascade Range in Washington is added for comparison. As the latter analysis is very similar to those of the Oregon rocks, an explanation for the mineralogic differences must be sought in the much greater size of the intrusive body in Washington. The large masses evidently permitted the retention of volatiles during the early stages of crystallization, and thereby favored the formation of hornblende and biotite, whereas in the small masses in Oregon, which have intruded into a necessarily porous group of rocks, the volatiles readily escaped and permitted the formation of augite. It was only in the late stages of crystallization that the volatiles had a marked effect upon the rock.

In the younger series that constitutes the High Cascades gray olivine basalt is the most prominent member, especially along the western margin. Typical specimens consist of a relatively even-grained, loose-textured aggregate of calcic labradorite or bytownite, augite, olivine, and magnetite. Some of the flows are distinctly porphyritic, and olivine and augite are particularly likely to occur as phenocrysts. In some the augites are poikilitic, inclosing large areas of the plagioclase network. In a comparatively few flows there is a little interstitial glass containing magnetite dendrites. In Table 3, an analysis of the olivine basalt is compared with analyses of similar rocks from the Modoc area and Steens Mountain. The rock of the Modoc area (called Warner basalt by H. A. Powers) may be closely related in age with at least part of the olivine basalt of the Cascade Range.

Table 3--Analyses and norms of typical rocks of the High Cascades and related rocks

Column	1	2	3	4	5	6	7	8	9
SiO_2	49.86	47.10	47.60	52.99	56.95	59.39	62.09	70.77	70.10
Al_2O_3	15.20	18.52	18.27	16.71	18.84	18.45	17.03	14.83	15.18
Fe_2O_3	1.69	Trace	1.91	3.80	2.06	1.79	2.38	1.35	1.78
FeO	10.50	7.91	8.93	3.55	4.28	3.90	2.69	1.25	1.09
MgO	6.25	10.89	6.54	6.95	4.37	3.13	3.08	0.64	0.74
CaO	9.43	11.98	8.70	8.49	7.45	6.29	5.65	2.12	2.27
Na_2O	3.08	2.33	3.11	3.56	3.89	4.29	4.10	5.07	5.15
K_2O	0.97	Trace	1.03	1.29	0.82	1.29	1.67	2.68	2.58
H_2O	0.24	0.10	0.80	0.59	0.31	0.42	0.13	0.33	0.19
H_2O-		0.18	0.33	0.18	0.19	0.10	0.04	0.07	0.10
TiO_2	2.50	0.90	2.20	1.18	0.79	0.41	0.65	0.38	0.48
P_2O_5	0.40	0.09	0.29	0.42	0.19	0.22	0.19	0.13	0.13
MnO	0.16	Trace	Trace	Trace	Trace	Trace	Trace	Trace	Trace
	100.27	100.00	100.08	99.92	100.18	99.77	99.84	99.88	99.97
				Norms					
Q				2.16	7.74	10.08	15.54	25.50	24.42
or	6.12		6.12	7.78	5.00	7.78	10.01	16.12	15.57
ab	26.20	17.82	26.20	29.87	33.01	36.15	34.58	42.97	43.49
an	24.46	40.03	32.80	25.85	31.14	27.24	23.07	9.45	10.56
ne		0.85							
wo	8.24	7.77	3.60	5.80	2.09	1.39	1.74		
en	10.20	4.90	4.80	17.40	10.90	7.80	7.70	1.60	1.90
fs	9.24	2.38	3.30	1.45	4.88	5.02	1.85	0.53	
fo	3.78	15.54	8.32						
fa	3.67	8.36	6.12						
mt	2.55		2.78	5.57	3.02	2.55	3.48	2.09	2.09
hm									0.32
il	4.71	1.67	4.26	2.28	1.52	0.76	1.37	0.76	0.91
ap	1.01	0.34	0.67	1.01	0.34	0.34	0.34	0.34	0.34

References for numbered columns as to rock, place, and analyst

1. Olivine basalt. Cupola Rock, Lost Creek, Lane County, Oregon. J. G. Fairchild, analyst.
2. Ophitic basalt. Laird's Ranch, Modoc area, California. W. H. Herdsman, analyst (Powers).
3. Basalt. Steens Mountain, Harney County, Oregon. W. H. Herdsman, analyst (Fuller).

4. Hypersthene basalt. Red Cone,
5. Hypersthene basalt. Anna Creek,
6. Hypersthene andesite. Wizard Island,
7. Hypersthene andesite. Palisades,
8. Hypersthene dacite. Llao Rock,
9. Lithoidal hypersthene dacite. Cleetwood Cove,

Crater Lake, Oregon
H. N. Stokes, analyst
(Diller and Patton).

No extensive chemical and petrographic study of the lavas of the large cones has been published, other than the classic study by Diller and Patton of the rocks at Crater Lake, which occupies the crater of Mt. Mazama. The analyses in columns 4-8 of Table 3 are taken as representative of the three types of rocks described by these authors. The basalts contain calcic plagioclase, augite, hypersthene, olivine, and magnetite. Some are nearly even-grained and others contain phenocrysts, principally of olivine, and most of them have a brown glass base. They have originated from small cones rather than from Mt. Mazama itself. Andesites make up the bulk of the remaining walls of the volcano and are represented in columns 6 and 7, Table 3. They contain

calcic andesine or labradorite, augite, hypersthene, magnetite, and glass. Their textures and their relative proportions of glass are variable. Dacite or rhyolite occurs with the lavas of Mt. Mazama. They contain phenocrysts of oligoclase, andesine, or even labradorite, hornblende, hypersthene, and augite in a glassy or partly glassy base. Analyses of these rocks are represented by columns 8 and 9, Table 3. The vast pumice field that is in the vicinity of Crater Lake and extends to the northeast for many miles should be as definitely regarded as part of the sequence at Mt. Mazama as should the last eruption which forms Wizard Island and consists of andesite flows. Hypersthene andesites and rhyolites and some obsidian appear to be characteristic of the large cones throughout the range.

Volcanic activity, after glaciation (Wisconsin?), is represented by the last two eruptions of Mt. Mazama, the black basaltic cones in the vicinity of the Three Sisters, and a rhyolite flow on the South Sister, as well as by small cones and flows in several other places in the High Cascades.

In summation, it may be pointed out that volcanoes have been active in the Cascade Range in Oregon from Eocene to Recent time. There is at least one distinct break in the area south of Mount Hood during which the volcanic rocks of the Western Cascades were deformed, cut by intrusive stocks, subjected to the effects of mineralizing solutions, and deeply dissected before the lavas of the High Cascades were extravasated. The lavas of the Western Cascades are separated into two groups--one that is characterized by black lavas, chiefly calcic andesites, with associated rhyolites, andesites, tuffs, and agglomerates, and another, mainly stratigraphically higher, that consists of gray calcic andesites, more sodic andesites, rhyolites, and associated pyroclastics. These rocks contain many alteration products, which resulted largely from contact-metamorphism and activity of subsequent vein-forming solutions. The rocks that form the High Cascades are characterized by a large mass of gray olivine basalt, large cones composed mainly of hypersthene andesite, rhyolite and pyroclastics, and small cones, some of them quite recent, of andesite, calcic andesite, basalt, and possibly other types. Chemically, the great bulk of the rocks, with the exception of the olivine basalt, is saturated with respect to silica. CaO is abundant, equalling the oxides of iron in calcic andesites, and K_2O is low, not exceeding Na_2O even in the most siliceous rocks yet analyzed. Mineralogically, the phenocrysts of feldspar range from bytownite to oligoclase; augite is the most abundant ferromagnesian mineral; hypersthene is abundant in the rocks of the High Cascades, but uncommon in the Western Cascades where it may be represented by chlorite pseudomorphs. Biotite occurs in a rhyolite at the base of the series west of Crater Lake and in a few dikes. Hornblende is limited to the siliceous rocks and is not abundant in the Western Cascades. Quartz phenocrysts are not common even in many of the rhyolite flows. Orthoclase is limited to interstitial material or replacement of plagioclase. Olivine is not abundant in the western Cascades, though it is represented by pseudomorphs in many flows. Usually the flows of the Western Cascades are much more altered than those of the High Cascades. In general, it appears that there have been no pronounced chemical or mineralogical trends during the accumulation of this tremendous pile of volcanic rocks, which probably accumulated during all the major epochs of the cenozoic. What may be regarded as an exception is the extravasation of the large mass of olivine basalt following a period of quiescence of unknown duration.

U. S. Geological Survey,
Washington, D. C.

ACTIVITY AT SANTA MARIA VOLCANO IN GUATEMALA

E. G. Zies

(Abstract)

Attention was again directed to the volcanic area of Central America and emphasis was laid on the opportunity presented in this region for carrying out a coordinated research on the problems of volcanology. The various volcanic centers are reasonably accessible and are not far removed from the laboratories that are interested in the analytical and synthetical phases of the problems. The manifestations are confined to a relatively small area and are sufficiently varied so that comparative studies can be made in the field. A fine opportunity therefore exists for co-

ordinating work in the laboratory and in the field. All students interested in volcanological phenomena must admit that the study of volcanism is as yet only in the descriptive stage; there is no generally accepted theory to account for volcanic activity nor does an empirical background exist on which to base such a theory.

Especial attention was directed to the activity at the volcanic dome of Santa Maria during February of 1933. It should be borne in mind that this Volcano has been continuously active for the past ten years. The fumarolic activity continues unabated and furnishes an admirable opportunity for studying the chemical changes that are taking place in the gases emitted from the dome and also for studying the decomposition of the extruded lava by the gases. Minor explosions accompanied by steam- and dust-clouds took place but no fresh lava has been brought to the surface. A detailed study, in the field and in the laboratory, of the volcanic manifestations found at Santa Maria should yield valuable information. When the results of such work are correlated with similar results obtained at the other volcanic centers in Central America it will be possible to build up the empirical background demanded in the elucidation of the problems of volcanological activity.

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

VOLCANIC HISTORY OF THE MAGDALENA DISTRICT, NEW MEXICO

A. H. Koschmann

(Abstract)

The Magdalena District in central New Mexico comprises the Magdalena Range and Granite Mountain which are block mountains of the Basin Range type. They consist of Carboniferous sedimentary formations on a pre-Cambrian basement and are covered by Tertiary volcanic rocks.

Volcanism in the District was preceded by considerable faulting, tilting, and uplifting very probably in early Tertiary time. The initial volcanic extrusion consisted of latite flows and tuffs now resting unconformably on the Granite Mountain fault-block in the northern part of the District. Subsequent extrusions consisted of alternations of andesites, rhyolites, and latites, and have a minimum thickness of approximately 4,000 feet. Graben faulting, probably in compensation for the effusion of the large volumes of lava, followed and some of the major faults were subsequently the sites of the intrusion of monzonitic and granitic stocks. Late lamprophyre and white rhyolite dikes in large numbers intruded the intrusive as well as earlier extrusive and sedimentary rocks.

As igneous after-effects, large volumes of silicifying solutions were welled up and the volcanic rocks in the southern part of the District have been extensively silicified and the Mississippian limestone has been in large part replaced by jasperoid. The upwelling of ore-depositing solutions followed and produced large bodies of replacement ore of lead and zinc.

More recently basalt flows have covered Quaternary gravels and, although none is now found within the District, they unquestionably also covered parts of the area before extensive erosion removed them. The basalt-flows mark the final phase of volcanism.

U. S. Geological Survey,
Washington, D. C.

SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

AND

EASTERN SECTION OF THE SEISMOLOGICAL SOCIETY OF AMERICA

PROCEEDINGS OF THE 1933 JOINT MEETING

Washington, D. C.
April 27, 28, and 29, 1933

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ADDRESS OF THE CHAIRMAN

Frank Wenner

At previous meetings of the Eastern Section of the Seismological Society of America, it has been the custom for the Chairman to make a general report of recent progress in seismology. However, Captain Heck, who is much better qualified than I to do this, will give a review of seismology in the United States, and I expect to have something to say on a particular subject later. This leaves me free at this time to follow my fancy, but I wish to mention a few items of progress and look somewhat into the future. In doing so, I trust that I shall not duplicate to any considerable extent what others may have to say later.

But first I wish to mention some matters pertaining to both of the organizations meeting jointly. The program is rather lengthy and promises to be of considerable interest. For this program we are indebted almost entirely to Secretary McComb, who, as I happen to know, has given careful consideration to the matter and liberally of his time. As our funds are very limited, he has done most, if not all, of the typing, while the number of letters he has sent out is in excess of 100. He therefore deserves our thanks and I personally wish to express my appreciation of his faithful and efficient services as Secretary of both organizations.

Reference has been made to limited funds and this applies not only to the Eastern Section of the Seismological Society of America but also to the American Geophysical Union. Membership dues in the Eastern Section have purposely been kept low so as not to deter anyone interested from becoming a member. However, it seems to me that our membership-list does not include all of those who would be interested if they really knew of the splendid work the Section is doing. Most of the money paid in dues is used in the publication of "Earthquake Notes." If the membership were larger, "Earthquake Notes" could be more widely distributed. May I suggest, therefore, that each of you make an effort to secure one or more new members, or, in case you know of anyone living outside the jurisdiction of the Eastern Section who might be interested, that you let them know they may subscribe to "Earthquake Notes." Also, in case you know of anyone interested in geophysics and who might be interested in becoming a member of the American Geophysical Union, I suggest that you send his name to Chairman N. H. Heck of the Union's Committee on Membership.

With reference to progress, mention should be made of the work of the Coast and Geodetic Survey, and especially its recently inaugurated program for the investigation of earthquakes within destructive areas. While this will be referred to in various papers which are to follow, I may state that a number of strong-motion instruments have been installed and provision made for their care. Also, other instruments have been constructed and are being installed. The instruments are of three distinct types, namely: (1) Very short-period seismometers giving quantitative data concerning the accelerations in the range of frequencies generally considered as causing the destruction of property with consequent loss of life; (2) displacement-meters, that is, seismometers having periods of from 5 to 10 seconds and low magnification; and (3) seismometers of periods from 1 to 3 seconds and low magnification. Each type of instrument is intended to give information supplemental to that obtained by the others. Too much praise cannot be given to Captain Heck and his associates for having a part of this equipment installed and in operation at the time of the southern California earthquake of March 10, 1933. The experimental data expected from the records made in Long Beach, Vernon, and Los Angeles presumably will be the first obtained in this country of significance to the structural engineers, and possibly they will be of more significance than any data obtained elsewhere. When all the instruments which have been constructed are in operation, we should expect more complete data if we be so unfortunate as to have a really severe earthquake in a region in which earthquakes are most to be expected. However, I would suggest that the development of instruments be continued. Now that some experimental data have been obtained, more definite predictions can be made as to how different types of instruments would respond to ground-movements similar to those at Long Beach on March 10. The instruments should be so designed that under similar conditions they would not be wrecked and that the record made by them would give data of value, otherwise an instrument may be maintained for 25 years or more and be wrecked just at the time it should function or give a record from which little or no information could be obtained. It is possible, also, that

other types of instruments might be used to advantage, and this is a matter deserving consideration. Dr. Gutenberg of the Carnegie Institution of Washington has been using an instrument which, according to his personal statement, is constructed as follows:

"Connection to the ground is made by two rather massive concrete piers separated a distance of 2 or 3 meters. Attached to one of the piers is an arm extending to the other pier and of such rigidity relative to its mass that the natural period is only a few tenths of a second. The arm supports a coil of insulated wire in the field of a magnet attached to the other pier. This coil is connected to a galvanometer so registration is similar to that of the Galitzin seismometer."

Just how this instrument is actuated may not be known definitely, but it is probable that it is actuated in part by accelerations but to a greater extent by deformations of the Earth. At any rate, an instrument could be so designed as to respond mainly to strains in the ground and only to a limited extent to accelerations. Instruments of this type are generally known as recording strain-gages. Such instruments, if suitably designed for the purpose, might give valuable information concerning distant earthquakes. Also, if suitably designed for the purpose, and located in the ground and in buildings in regions of destructive earthquakes, they would in time give information of value to the structural engineer.

In closing, I wish to speak of the enthusiastic and splendid cooperation between the Coast and Geodetic Survey, the Jesuit Seismological Association, the Carnegie Institution of Washington, Science Service, all institutions operating seismological stations, various individuals, Massachusetts Institute of Technology, and especially the faculty of Georgetown University, whose members were largely responsible for the earlier work in seismology in this country, and who are offering their facilities for our meeting on April 29, 1933. My only regret is that we do not have any considerable cooperation from those engaged in geophysical prospecting. Much work has been done along this line, and no doubt much valuable information collected, but it is not being published to any considerable extent. In this work, the speed of propagation, or time-travel, is of prime importance, especially near the surface. It is also of importance to seismologists generally since, if directions are to be obtained from a single station, a knowledge of the velocities for different frequencies in the vicinity of the station would be of material assistance. I, personally, have been given some of this information, but unfortunately it must be kept confidential, at least for the present.

U. S. Bureau of Standards,
Washington, D. C.

A REVIEW OF EARTHQUAKES OF THE PAST YEAR

Joseph Lynch, S.J.

During the year the number of major earthquakes recorded reached the usual annual average. Fifty epicenters were determined by the Coast and Geodetic Survey or the Jesuit Seismological Association, or both. Though this number was only slightly in excess of that of the previous year, the distribution over months was very different. In 1931, July and August were the heaviest months--9 in July and 7 in August. In 1932, these months were the lightest--3 in July and 3 in August. In 1931 there was a definite peak in midsummer, trailing off to a slump in December when there was none. In 1932, what little slump there was occurred in midsummer, but no month had less than three major quakes. June and September were the heaviest months with 7 quakes apiece, November comes next with 5 (none of these being connected with the Democratic landslide of that month), March comes next with 4, and so on.

In the matter of geographical distribution, several peculiarities are worth noting. In general they follow the beaten track, being confined to the equatorial belt and more or less to the Pacific Basin. But while one generally expects a greater number in the northern than in the southern hemisphere, the ratio of north to south was unusually high this year--41 in the northern hemisphere and only 9 in the southern. Moreover, whereas the most southerly epicenter was only 39° south, there were half a dozen northern epicenters around the 60's.

A similar peculiarity is to be noted in the longitudinal distribution--35 epicenters occur west of Greenwich and only 15 east of Greenwich. Charting of epicenters shows how the scene of the disturbances has shifted since last year. Such charting included: (1) General map showing epicenters over a period of 20 years; (2) quakes of 1931-32, centering around Japan and Australia; (3) quakes of 1932-33 centering around Mexico. The shift of disturbances from 1931-32 to 1932-33 may be noted from general summary of occurrence as follows: (a) Atlantic Ridge--several in 1931-32, none in 1932-33; (b) North Australia--numerous in 1931-32, scarce in 1932-33; (c) Central America--moderate in 1931-32, very numerous in 1932-33; (d) No. 37 (Nevada) and No. 40 (near Madagascar) are unusual locations.

In the number of casualties the year was by no means a heavy one, though heavier than the previous year which was unusually mild. Two years ago 4,000 people were killed, chiefly in the Nicaraguan, Italian, and New Zealand disasters. A year ago less than a hundred were killed, chiefly in Cuba and the Solomon Islands. During the past year about 2,300 were killed: 1,500 in Japan; 350 in Greece; 280 in China; 130 in California; and the rest mainly in Mexico. As stated in "Earthquake Notes," the quake of December 25, 1932, in China is interesting in view of the fact that reports of the disaster did not reach the outside world till nearly two months after the publication by the Coast and Geodetic Survey of the epicenter and prediction of almost certain disaster.

The two quakes of most interest were those of March 3 in Japan and of March 10, 1933, in California. The former was the most disastrous of the year, killing 1,500 people, while the latter was our unfortunate family disaster. Comparisons of the records of these two show that the California quake was an extremely mild one, despite the disaster.

Fordham University,
New York, New York

THE FIRST PRELIMINARY WAVES OF THE CALIFORNIA EARTHQUAKE OF JUNE 6, 1932

Perry Byerly and Neil R. Sparks

On the morning of June 6, 1932, at 44 minutes past midnight the region about Humboldt Bay was severely shaken by an earthquake which attained a maximum intensity of VIII on the Rossi-Forel scale. One death and a number of injuries were caused by the shock. It was felt as far north as Coos Bay, as far south as San José, and as far east as Sierra County. Records from the following stations were collected for a study of the earthquake: Ukiah, Berkeley, Tinemaha, Santa Barbara, Pasadena, Riverside, La Jolla, Bozeman, and Tucson.

The writers agree with A. Mohorovičić that epicenters are best located by records from stations at intermediate epicentral distances, say between 6° and 16°. An epicenter is well located if the arrival-times of the first P at all stations within these distances lie on a smooth curve. In practice this smooth curve is a straight line within the present limits of accuracy of time (say one second).

In the present study the epicenter was so located. The slope of the straight line indicated a speed of 7.7 km/sec. The position of this epicenter was 124° 30' west longitude, 40° 45' north latitude. This lies on the prolongation of a fault plotted on the Geomorphic Map of California. This fault was ruptured at the time of the great 1906 earthquake. On the Geomorphic Map it is plotted as a continuation of the San Andreas Fault. However, it is usually thought of now as a parallel fault since it does not line up with the trace of the San Andreas farther south.

An effort was made to identify later arrivals in the first preliminaries. Their existence is in no doubt since the Wood-Anderson records available from many of the stations show them very clearly. Correlation of the later arrivals at the various stations is more difficult. When plotted they show scattering. An effort was made to correlate them by similarity of wave-form and general appearance on the record. This led to the identification of three waves of speed 7.7 km/sec. The second, $P'_{7.7}$, arrives 2 seconds after the first, $P_{7.7}$. The third, $P''_{7.7}$, arrives 4.5 seconds after $P_{7.7}$. Lines are drawn for waves of speed about 7.4 km/sec and 7.0 km/sec.

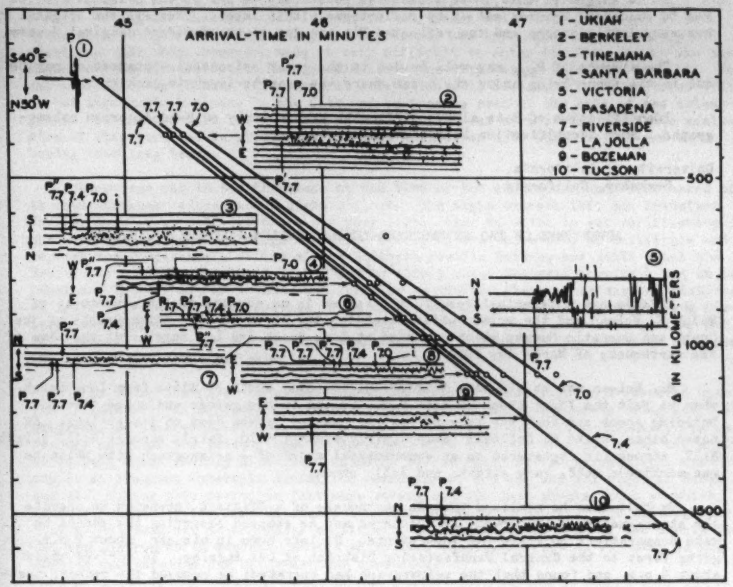


Fig. 1--Travel-time curves and records, California earthquake, June 6, 1932

We feel that justification, if such there be, for drawing travel-time curves for later arrivals resides in similarity of wave-form at various stations. In Figure 1 we present the travel-time curves together with the records on which they are based.

The beginning of the first P is very weak at some stations and a few of our readings of this wave may be criticized on this basis. However, there was a sufficient number of good arrivals to place the curve, and the other readings were made independently by each of us and checked. The grounds for correlating later arrivals may be judged from Figure 1. We hope that the reader of this paper will point out the various correlations and criticize them. The similarities at Berkeley, Pasadena, Riverside, and La Jolla are particularly marked.

The writers feel that further progress in the study of earthquake travel-time curves must result from studies of individual shocks. If the arrivals for many earthquakes are plotted on one diagram, a maze of points results, the different errors for the different shocks producing confusion. Let us not average our data, but rather draw conclusions from each shock separately and then average our results.

It is well to associate points on the travel-time curve by similarities on the records rather than by drawing some conventionalized system of lines through them in some averaged position. True, the latter system is easier and the former is perhaps often impossible--still the attempt is worth while and may lead us from what threatens to be serious confusion.

In Figure 1, which the writers offer for whatever it may be worth, we draw three parallel curves corresponding to waves of speed 7.7 km/sec. In his study of the California earthquakes of November 28, 1929, one of us found a similar tendency for parallel lines.

It is suggested that these successive pulses may be due to the original P-waves and to secondary P-waves set up by reflections within layers. Perhaps the original P has very little energy and the reflected P's are due to the incident original S-wave.

The absence of $P_{6.6}$ may well be due to the great epicentral distances or may be due to the focus being under the ocean where the granite-layer is lacking.

Identification of S is always difficult, particularly on Wood-Anderson seismographs. Such identification is not attempted here.

University of California,
Berkeley, California

ADVENTURES OF TWO SEISMOGRAPH-TENDERS DURING A SEVERE EARTHQUAKE

A. K. Ludy

This is not a technical report, but rather is an account of the adventures of Ralph S. McLean and the writer while attending the strong-motion seismographs of the Coast and Geodetic Survey which operated at Long Beach and Los Angeles at the time of the earthquake of March 10, 1933.

Mr. McLean was at his home in Brea, California, about 30 miles from Long Beach, when he felt the first shock at 5:55 p.m. He was in his garage and noted that the building shook and that the body of his car bounced up and down on its springs. He noted other shocks as follows: 6:05, fairly strong; 6:10, fairly strong; 6:11, slight; 6:17, strong (it registered on an experimental model of a seismograph with which he was working); 6:22, very slight; and 6:31, strong.

By this time he realized that an earthquake of sufficient intensity to operate the strong-motion seismographs had occurred and he stopped observing the shocks to make preparations to visit the instruments. He left home in his car about 7 p.m., going first to the Central Manufacturing District of Los Angeles. He arrived there about 8 p.m. and found that the seismograph had operated; he removed the record, tested the operation of the instrument, and placed a new sheet on the drum. He then started for the Subway Terminal in Los Angeles, but in the excitement left his keys at the Central Manufacturing District station and had to return for them. Here he was told that another shock had been felt, so he again changed the records on the seismograph-drum.

The building in which the seismograph is housed is a concrete structure with an ornamental tower which contains a large concrete water-tank. The pipe connections under the tank were damaged by the earthquake so that considerable water leaked out of the tank into the building before it could be drained into the sewer. Most of the glass in the windows of the tower was broken. Later it was learned that the counterweight of the elevator in the building had swung with sufficient force to bend its steel guides several inches out of line. A brick building across the street from this one had its parapet walls thrown down into the street. Where these walls reached the street intact, the tops were toward their own building.

Mr. McLean then visited the Subway Terminal, found that the seismograph had operated, and changed the record-sheets. He made a quick superficial examination of the building for damage and found none. He then proceeded to Long Beach, where he arrived about 11:50 p.m. He serviced the seismograph here as at the other stations and made a hasty examination of the building. The seismograph is housed in the Public Utilities Building owned by the City of Long Beach. It is a concrete structure and suffered no damage, although we saw a small crack in one of the huge supporting columns in the basement, which may or may not have been caused by the earthquake. Many of the nearby buildings were in ruins. Mr. McLean returned home from Long Beach after one o'clock in the morning.

Almost immediately after the first earthquake-shock, Long Beach was placed under martial law. The United States Fleet was in the harbor and many sailors were detailed to patrol the city. The Red Cross, American Legion, and other organizations were

called upon to assist the city authorities in helping the victims and protecting property. During all the week that I spent in Long Beach and vicinity I heard of no cases of looting or thievery, though much property was left exposed and readily accessible. All this, however, made it very difficult to enter the City, as it was the object of the authorities to have people leave the City rather than come into it. In spite of this, Mr. McLean after several delays was able to convince the sentries that he had legitimate business in the City and he finally reached the site of the seismograph. During the next few days the patrols became even more strict about the admission of strangers and we always had the same conditions with which to contend when coming into Long Beach.

The writer was in San Francisco at the time of the earthquake and first heard of it from newspaper extras about eight o'clock. The night express left San Francisco for Los Angeles at 8:30, so there was very little time in which to get verification of the reported earthquake through Professor Byerly at the University of California and through the Dispatcher's Office of the Southern Pacific Railway and still catch the train; yet all this was accomplished and by nine o'clock the next morning I was in Los Angeles. There I met Mr. McLean and together we visited the two Los Angeles stations to again service the seismographs. When we arrived at the Central Manufacturing District we found the building closed and roped off and all persons ordered to stay out. But the call of science was stronger than the fear of supposed danger and we obtained the keys to the place and went in.

This being the first time that the strong-motion seismographs had operated under the influence of an earthquake, and the development of the instruments being still in progress, we desired to find out, if possible, just what earthquake-intensity was necessary to cause the seismographs to operate. With that end in view, after our arrival in Long Beach shortly after noon on March 11, we stood by the seismograph, examining it at frequent intervals during the remainder of the day and all night of March 11 and 12. During this period we felt many strong and distinct shocks, none of which, however, were of sufficient intensity to cause damage to property. The seismograph-starter had been set to a greater sensitivity than normal, yet none of the shocks felt set the instrument in motion. Shocks which were distinctly felt as far away as Los Angeles and Pasadena did not start the apparatus.

By nine o'clock on the morning of March 12 it was decided that we could gain nothing more by observing the seismograph and we proceeded to Pasadena, where H. O. Wood kindly permitted us to use the dark-room facilities of the Seismological Laboratory for the development of the records we had taken from the seismographs. We watched in some suspense for the appearance of the lines during development, and we were happy to find that the grams appeared to be good and to give promise of showing much useful information.

U. S. Coast and Geodetic Survey,
Field-Station,
San Francisco, California

THE CEDAR MOUNTAIN, NEVADA, EARTHQUAKE OF DECEMBER 20, 1932

Vincent P. Gianella and Eugene Callaghan

An earthquake of major intensity originated in the area east and northeast of Mina in southwest central Nevada on December 20, 1932. The principal shock occurred at about $10^h\ 10^m\ 04^s$ p.m. P.S.T., and was definitely perceptible over an area of some 400,000 square miles, including Nevada, the greater part of California, and parts of Oregon, Idaho, Utah, and Arizona. A circle including such outlying places as Rawlins, Wyoming; Cottonwood, Idaho; San Diego, California, and Klamath Falls, Oregon, would have an area of nearly a million square miles. It thus ranks as a major American earthquake, yet is remarkable in that there was no loss of life and very little damage to property. The explanation for this condition must be sought in the sparse population (scarcely a dozen people in the epicentral area), location of almost all structures on bedrock, lack of water-soaked alluvium, and probable great depth of origin of the shock.

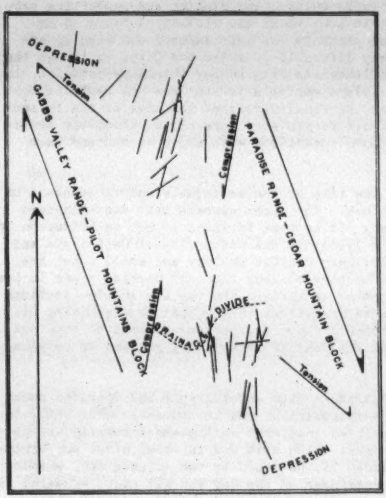


Fig. 1--Diagram showing average trend of the majority of rifts in their relative mapped positions and their relation to main topographic features and to a possible arrangement of stresses that might have produced them, thereby causing the earthquake

Accessory shocks include a foreshock, which came about 40 minutes prior to the main shock, and thousands of aftershocks. The latter were reported on April 23 to be still continuing though with greatly reduced intensity and frequency. The curve of aftershock-frequency calculated from records of the Wiechert seismograph at Reno is very similar to those derived by Japanese seismologists. A roar accompanied the inception of the principal shock, and the aftershocks, where observed on hard rocks, were preceded by a rumble like distant thunder. As the sound-waves are of the same physical nature as the preliminary longitudinal waves, it is believed that the two are the same, but actual proof should be sought.

The effects of the main shock included those usual in such disturbances. People were badly frightened and many suffered from nausea. Cattle stampeded at Fingerrock Camp, in the epicentral area. Some springs ceased to flow, some had increased flow, and others were unaffected. Boulders were shaken from cliffs and hillsides. It was noted that balanced boulders were generally not overturned whereas unbalanced boulders were displaced if the bond holding them was broken. In at least one place boulders on nearly flat ground were overturned in their beds and in many places the surface-layer of soil was thoroughly shaken as though harrowed. Damage was confined to demolition of a stone cabin and an adobe cabin, cracks in the few brick or concrete structures in the vicinity, dislodged chimneys, damage to ore-treating plants and mines, broken dishes and other articles thrown from shelves, and minor items.

The principal shock of the earthquake accompanied the formation of a group of tension or open faults or rifts over an area 38 miles long and from 4 to 9 miles in width in the lowland between the Gabbs Valley Range and Pilot Mountains on the west and the Paradise Range and Cedar Mountain on the east. The rift-area ends to the north in the south side of Gabbs Valley and to the south in the depression north of the Monte Cristo Range. The lowland is a partly dissected pediment-surface on Tertiary lake-beds (Esmeralda formation) and volcanic rocks with a thin mantle of detrital material. The contiguous mountain-ranges are composed largely of Mesozoic sediments and intrusive rocks with some Tertiary volcanic rocks. In many places the rifts follow sharp breaks in slope or the margins of low hills, indicating that they are related to earlier faults. Altogether, some 60 rifts, both large and small, were found, but undoubtedly many more escaped notice because of the snow in many places and because of the short time the weather allowed for the field-investigation.

Individual rifts are from a few hundred feet to nearly four miles in length and consist of a zone of fissures that may range from a few feet to several hundred feet in length. The rifts range in width from a few inches to nearly 400 feet. The rifts form an en echelon pattern in the rift-area, as shown in Figure 1, as the greater number have an average trend of north 11° east, whereas the direction of the rift-area is north 21° west. The strongest rifts occur in the southern part of the area. Some of them have a sigmoid form, and sharp turns and zigzags are common.

The fissures in the rifts have some remarkably uniform features. Long, strong fissures are in the direction of the rift, but weak fissures are at an angle, generally

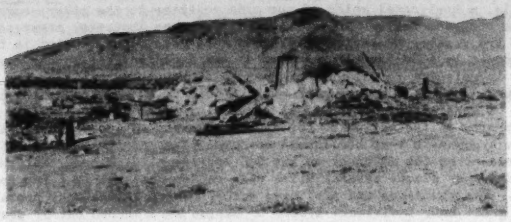


Fig. 2--Ruin of stone-cabin at Fingerrock Camp at west side of rift-area [This is one of two buildings completely demolished by the earthquake, so far as the writers are aware; the relative instability of cabin was due in part to the fact that the shaped stones were on edge rather than flat]

from 5° to 40°, to the direction of the rift. Consequently most of the rifts, particularly the weaker ones, consist of an en echelon belt of fissures which trend to the northeast of the direction of the rift, except in those places where the rift trends to the northeast in excess of 35°. So far as could be determined all the fissures are vertical, with the possible exception of the west wall of the large graben in the rift in the southern part of the area. Vertical displacement is common to almost all the stronger rifts and the throw may be either to the east or the west. It is generally less than a foot, except on the walls of grabens where it may be as much as four feet. Horizontal movement is indicated by compression-ridges athwart the direction of the rift, en echelon pattern of fissures, and actual displacements of as much as 34 inches, all indicating a relative southward shift of the east side. Grabens are common features of the stronger rifts and may be as much as a hundred feet in width between individual walls, which may be as much as four feet high. Most of the grabens are less than 15 feet wide and less than 1 foot deep. Their length is generally less than 100 feet.

A clue to the direction of the major movements producing the earthquake and the system of tension-faults is furnished by the pattern of the rifts within the rift-area and the pattern of the fissures and other features within the rifts. It should be emphasized that the rifts, certainly the larger ones, are primary features, for the bedrock is exposed in the major breaks and they die out in soft alluvium. It is noteworthy that the rifts have an average direction of north 11° east for the greater number as compared with a direction of north 21° west for the rift-area, and that there is striking uniformity of pattern of fissures, a tensional or open condition of most of

Fig. 3--Fissure showing three feet of vertical displacement near north end of Cedar Mountain [The bedrock (Esmeralda lake-beds) appears in the wall of the fissure]

the fissures, and a tendency for an actual relative southward movement of the east side of the rift. In general, the rift-area is an en echelon tension fault-zone, as shown in Figure 1. It is believed that the usual explanation for en echelon fault-zones--that is, a horizontal shift of one side relative to the other--corresponds very well with the observed facts. The resolution of forces indicates compression in the direction of the greater number of rifts (north 11° east) and tension in the opposite direction induced by a horizontal movement of the Paradise Range-Cedar Mountain block to the south in relation to the Gabbs Valley-Pilot Mountains block on the west, as shown in Figure 1. This conforms with explanations of en echelon faults in Oklahoma and Montana. A possibility of torsional stress involving uplift might be entertained, but the uniformity of indication of horizontal movement on individual rifts is more in line with the hypothesis that horizontal movement is responsible for the features observed. It resembles the movement on the San Andreas rift, except that the movement was distributed over a zone several miles wide rather than within a few feet or a few hundred feet. The abundance and prolonged occurrence of aftershocks probably indicates that a great many individual blocks or masses were thrown out of equilibrium.

University of Nevada,
Reno, Nevada

EXPERIENCES OVER A SUBMARINE EPICENTER

Charles Bittinger

The United States Fleet returned on March 9, 1933, from the battle maneuvers to remain a few days in the harbor of San Pedro. The 10,000-ton cruiser U.S.S. Louisville, to which I was detailed, anchored about three miles southeast by south from the Long Beach Navy Landing.

In the late afternoon of March 10, I was seated in my stateroom making some color-filters when suddenly the ship started to vibrate in a vertical plane in a most startling manner. The floor of my stateroom seemed to move up and down about an inch, five or six times a second. Not knowing the cause of this disturbance, the thought which entered my mind was that the steam-turbines had run away and the propeller-shaft had buckled out of line.

I went on deck and was informed it was an earthquake. No damage as far as I know was done to the structure of the ship.

By courtesy of the United States Navy Department, the following extracts from the records of the U.S.S. West Virginia, other United States vessels, and the Naval Air Station at San Diego are quoted:

"Friday, March 10, 1933--. . . . . Ship shuddered from stem to stern from effect of earthquake-shock between 17^h 55^m and 18^h 00^m. At first the shock was believed to be a magazine-explosion, but news of the actual quake was soon received over the radio. Recurring shocks were felt the rest of that day. Note on barograph-trace three severe shocks which made time-marks on the trace. Lighter ones failed to record. . . . .

"U.S.S. Lexington recorded 29 distinct tremors during the four days. All ships in San Pedro recorded shocks. The Naval Air Station at San Diego recorded three severe shocks."

Navy Department,
Washington, D. C.

EARTHQUAKES OBSERVED WITH A TELESCOPE

Earl L. Williams

Earthquake-waves originating at a considerable distance have been observed by means of the motion of the sensitive levels attached to the zenith-telescope of the International Latitude Observatory, Gaithersburg, Maryland. This telescope is regularly employed in making observations for variation of latitude.

On the night of April 26, 1933, the sensitive bubble of this instrument was observed to make not less than five to-and-fro excursions of approximately 2.0 amplitude, in the north-south direction. The levels in question are usually read to 0.1 of arc. The time checked well with the arrival of waves from the Alaska earthquake-epicenter, nearly 4,000 miles distant.

Less well observed, but of still greater movement, were the bubble-oscillations also observed at the time of the Nevada earthquake of December 20, 1932. On this occasion the star-images were believed to be temporarily more turbulent, possibly indicating a motion of the pier from the vertical.

International Latitude Observatory,
U. S. Coast and Geodetic Survey,
Gaithersburg, Maryland

EPICENTER-DETERMINATION--A DISCUSSION OF METHODS

R. R. Bodle

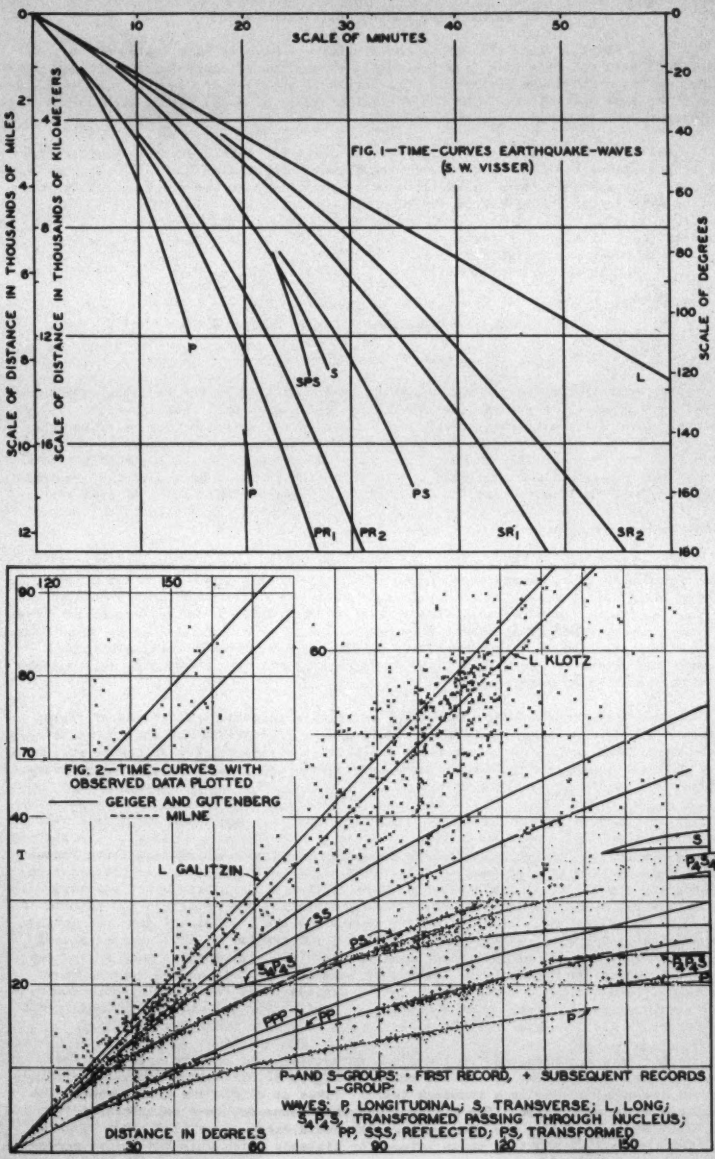
The problem of epicenter-determination is complicated by the fact that the principal wave-types which are used do not follow definite rules. They apparently follow general rules which have been observed and recorded, thus forming the basis for the travel-time charts or curves in use to date. The deviation of seismic wave-transmission from the general rule has been under careful examination with the result that Scrase has discovered and published a very promising solution in the form of variable curves. They are based on varying depth of foci. The various depths of foci are associated with changes in the characteristic of the curves. This development is outlined by Figures 1 to 3.

Figure 1 is one of the several standard travel-time curves now available. The most dependable portions are those representing the travel times for P and S, the others being of secondary importance in epicenter-location. Of the two phases, P and S, the P-phase is the most dependable when it is well defined on the seismogram. The S-phase is less dependable, principally because it is often complicated by waves from earlier phases. The fact that there are a half-dozen or more of these standard travel-time curves in use is in itself evidence that the task of sifting seismographic data has not been completed.

Figure 2 shows data from a number of earthquakes plotted against one of these standard curves. A glance at this Figure is enough to convince one that there is more to be done. The small dots and crosses indicating phase-times are so scattered that it is not at all surprising that so many people have developed curves which are very similar but seldom in complete agreement.

Figure 3 shows Scrase's solution. According to this chart the (P-O) intervals as well as the (S-P) intervals decrease with an increased depth of focus. I shall not discuss the curves further at this time except to say that the solution seems reasonable and in fact is gaining considerable favor among seismologists. If the solution is correct, one is led to ask, how can a curve of that sort be used with facility? The curves represent only general conditions and are not specific. In the opinion of the speaker, one of the most satisfactory ways is to use the P-phase data and match them against a P-curve. It will be noted that the character of the P-curves according to Scrase are quite similar for distances over 1,000 kilometers--more so, at any rate, than those for the S-phase. With this in mind, would it not be reasonable to determine distances by using (P-O) and assume various times for O until satisfactory intersections are obtained? Such a scheme is in effect a "cut-and-try" method. At the Survey it has been applied with good results using the following procedure.

As the data are received for immediate epicenter-location purposes, they are tabulated on forms similar to the one shown in Figure 4. Distances for the (S-P) intervals are tabulated using a standard table. Times at origin are then computed and tabulated and a mean taken. New distance determinations may then be tabulated for P-O, O in this case being the mean value. One could carry it still further by using the (S-O) intervals, plotting those values for distance which give the better agree-


SCALE OF MINUTES
SCALE OF DISTANCE IN THOUSANDS OF MILES
SCALE OF DISTANCE IN THOUSANDS OF KILOMETERS
SCALE OF DEGREES
FIG. 1—TIME-CURVES EARTHQUAKE-WAVES
(S. W. VISSER)
P
P
SPS
S
L
PS
PR1
PR2
SR1
SR2
L KLOTZ
L GALITZIN
FIG. 2—TIME-CURVES WITH
OBSERVED DATA PLOTTED
GEIGER AND GUTENBERG
MILNE
P-AND S-GROUPS: · FIRST RECORD, + SUBSEQUENT RECORDS
L-GROUP: x
WAVES: P, LONGITUDINAL; S, TRANSVERSE; L, LONG;
PP, SSS, REFLECTED; PS, TRANSFORMED
DISTANCE IN DEGREES

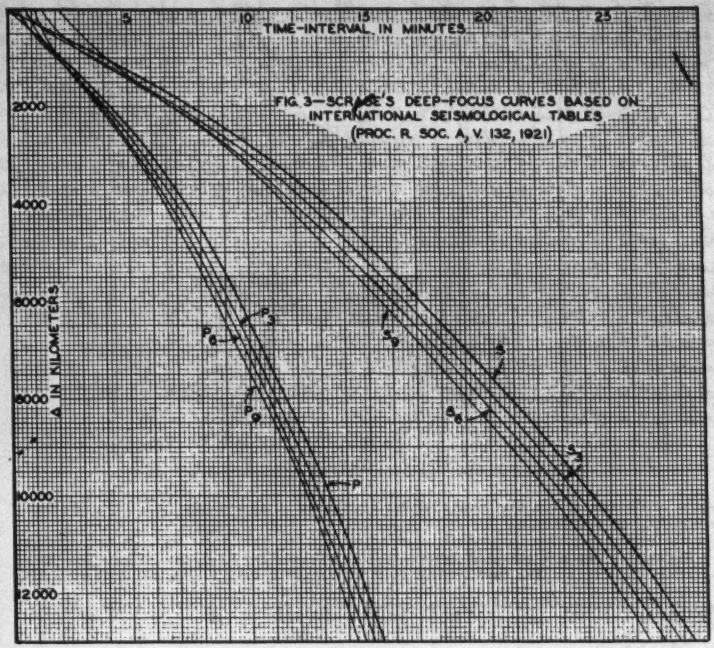


FIG. 3—SCRASE'S DEEP-FOCUS CURVES BASED ON INTERNATIONAL SEISMOLOGICAL TABLES (PROC. R. SOC. A, V. 132, 1921)

ment for arc-intersections. When these values fail to give satisfactory intersections, the data are plotted on coordinate paper (Fig. 5), using the values for distance appearing in the (P-O) column (values in the other column may be used equally well). A standard or special travel-time curve on similar cross-section paper is then placed directly behind the first sheet and the origin placed at any desired value for time at origin (as indicated by the dotted line in the Figure). A tabulation of the distances for each station is then made, using the times of the P-phases. This is done by estimating where the plotted point for the P-phase at any station would contact the adjustable P-curve in terms of distance. The arcs are then swung on the globe. From an inspection of the intersection one can usually learn whether the distances used are too long or too short. A new time of origin may then be adopted to suit and the process repeated. Usually two or three trials will bring the desired results, especially if the trial arc-intersections can be preserved for examination. This may be done if tracing paper and some form of Scotch tape are available.

This method may be followed still further by using different travel-curves until one is found which gives the best results. Special curves may be constructed where there are sufficient data on a single earthquake, and these may be used as a basis for future shocks in the same region. Just how far this latter scheme will work out the speaker cannot state definitely at this time, but sufficient evidence has been obtained to indicate it is practicable in some regions. It has worked well for shocks in the

December 21, 1932, G.M.T. (20h P.S.T.)

Station	Ph.	h m s	Ph.	h m s	Ph.	h m s	Ph.	m s	Ph.	h m s	Δ S-P	h m s	Δ P-O
Chicago	iP	6 15 N	iS	6 19 26	iL	6 22 28					2600	6 10 22	2667
New York	eP	6 16 49	iS	6 22 N							3644	6 10 05	3789
Georget.	eP	6 16 29	S	6 21 38	L	6 23.0					3400	6 10 06	3533
SPO	iP	6 12 24	iS	6 N 20	L_2	6 14 S_2					1167	6 09 44	1178
Tucson	iP	6 12 14	iS	6 14 04		Azimuth 322°					1111	6 09 46	1100
Michigan	iP	6 15 48	i	6 16 24	iS	6 20 36	i	6 21 54	L	6 23 00	3100	6 09 50	3033
St. Louis	iP	6 14 48	iS	6 18 57	i	6 19 01	e	6 20 28	eL	6 21 38	2444	6 09 59	2489
Pasadena	iP	6 11 16	i	6 11 30	i	6 11 38	i	6 12 22	iS	6 12 31	Too many portables		
Sitka	iP	6 15 03	iS	6 19 08	L	6 22.1					2522	6 09 57	2514
Ottawa	P	6 16 33											3178
Ukiah	P	6 11 13											
Tinemaha	iP	6 10 35											
Ataiwee	iP	6 10 42											
St. Barbara	iP	6 11 15											
Riverside	iP	6 11 7											
La Jolla	iP	6 11 34											
											Mean O	6 09 55	

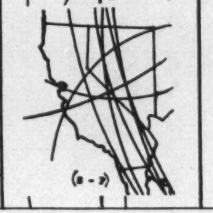
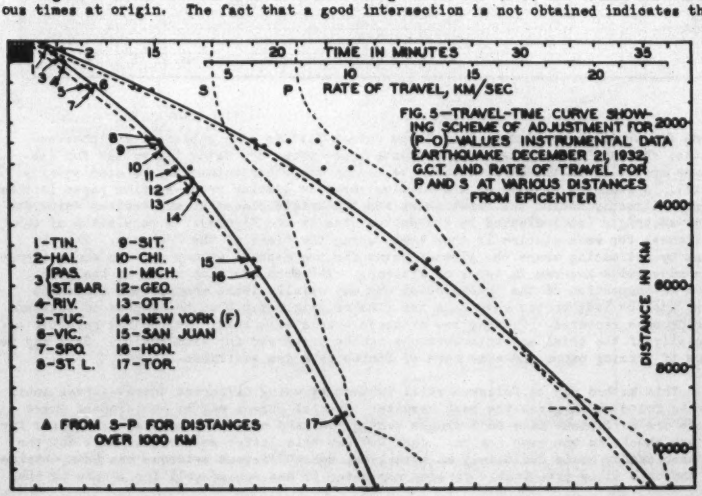


Fig. 4--Specimen determination of epicenter-location

region of Colima on the west coast of Mexico, while it apparently failed for shocks in the Gulf of California.

Figure 6 shows how the arcs intersect using values for (S-P) and trials for various times at origin. The fact that a good intersection is not obtained indicates that



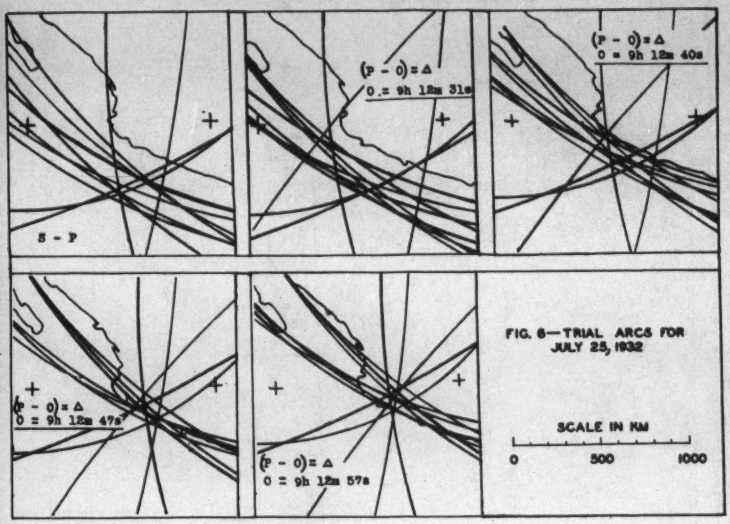


FIG. 6—TRIAL ARCS FOR JULY 25, 1932

the proper shaped time-curve has not been used.

Figure 7 shows a special curve for the region and the intersection obtained for the shock of July 25, 1932. It will be noted that these arcs are turned from points fairly well scattered in azimuth--La Paz being to the southeast, with San Juan and Honolulu to the east and west and Sitka to the north.

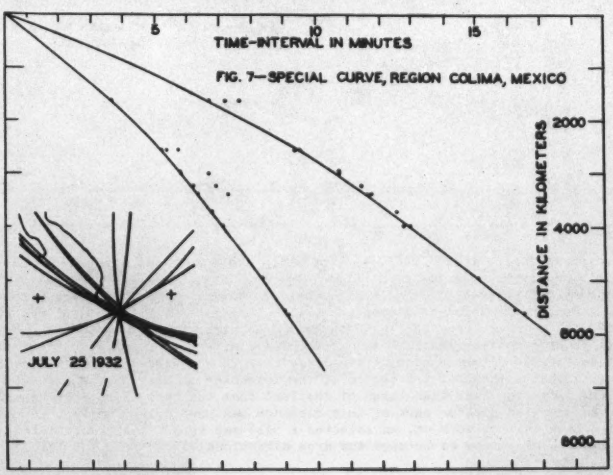


FIG. 7—SPECIAL CURVE, REGION COLIMA, MEXICO

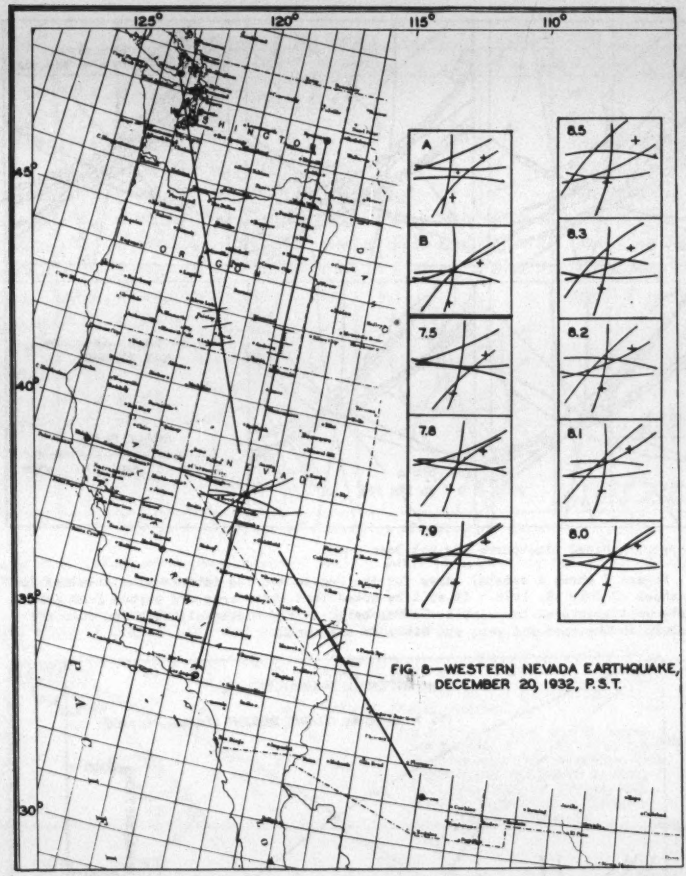


FIG. 8—WESTERN NEVADA EARTHQUAKE, DECEMBER 20, 1932, P.S.T.

Need occasionally arises for locations which are more exact than may be consistently obtained by methods just described. Two such instances have occurred during the past year. The first was the shock in western Nevada which took place December 20, 1932. Records of this shock were unusual in that most of the stations reporting found difficulty in interpreting the S-phase. This was evidenced by the lack of agreement in origin time (see Fig. 4). The P-phase data were finally resorted to as the most dependable. Examination of available data showed also that there were stations well distributed about the region of the epicenter at distances within 1,500 kilometers. Advantage was then taken of the fact that the general rate of travel for the P-phase over the greater part of this distance was practically uniform as shown in Figure 5. With this to work on, we selected a base-map known to be reasonably accurate for the general distances to be used and drew directional lines from the stations

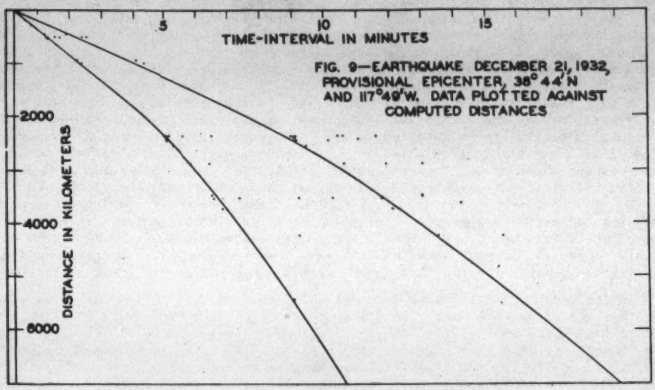


FIG. 9—EARTHQUAKE DECEMBER 21, 1932, PROVISIONAL EPICENTER, 38° 44' N AND 117° 49' W. DATA PLOTTED AGAINST COMPUTED DISTANCES

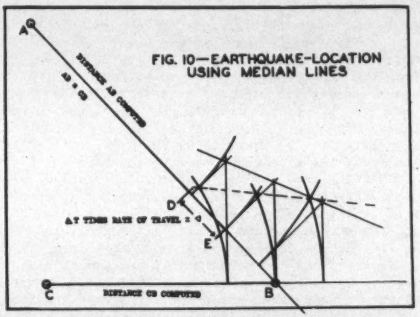


FIG. 10—EARTHQUAKE-LOCATION USING MEDIAN LINES

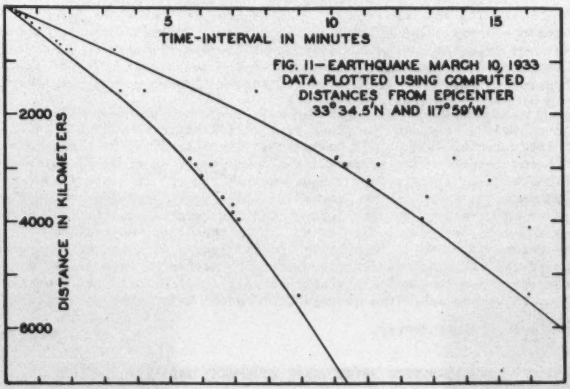


FIG. 11—EARTHQUAKE MARCH 10, 1933 DATA PLOTTED USING COMPUTED DISTANCES FROM EPICENTER 33° 34.5' N AND 117° 59' W

toward the epicentral region (Figure 8). The times of arrival for P at the five selected stations were tabulated. The earliest time was then subtracted from that for each of the other four stations. Now it seemed that if we selected the correct rate of travel, we could multiply each time-difference by that rate and thus obtain distances which when measured on the direction-lines from the stations would terminate at points equidistant from the epicenter--that is, if the exact epicenter were known, a circle with radius equal to the distance to the nearest station would pass or very nearly pass through the points located on each of the directional lines. Trial arcs were swung using an approximate radius and the center estimated as in A. Using a radius equal to the distance from this point to the nearest station, a new set of arcs were drawn as shown at B. This radius was adopted and trial arcs drawn from points on the directional lines corresponding to various rates of travel from 7.5 km/sec to 8.5 km/sec. A comparison of the arcs then indicated that the one for 8.0 km/sec was probably the better. The epicenter corresponding to this intersection was therefore adopted as 38° 44' north and 117° 49' west. Field-examination has shown it to be reasonably correct. Figure 9 shows how the data appeared when plotted against a standard travel-time curve. Note how they depart from the P-curve at the greater distances.

In the case of the shock in southern California on March 10, 1933, there was difficulty since it was not well recorded at the more distant stations. Trial by arc indicated that there was need for better longitude-control. Median lines, let us call them, though strictly they are not, were used. Actually the lines are the locus of a point which is always at a given distance farther from one station than the other, thus meeting the requirements for constructing an hyperbola. The difference in the lengths of the radii used is determined by the difference in the times of arrival at the two stations multiplied by the rate of travel at that general distance. Figure 10 indicates the procedure. A large-scale base-map was used. Owing to its inaccuracy for distances, say, greater than 1,000 kilometers, it was necessary to compute the great-circle distances from the various stations to a station near the epicentral region--in this case, Pasadena, or point B on the Figure. The difference in the distance from two stations to B was laid off on the longer, measuring from B--the distance here being BD. Now that leaves AD = CB. It should be stated that the station-pairs selected must have as small a difference as possible in the times of the P-phase arrivals. The size of this time-interval has a definite bearing on the accuracy of the results. The time-difference multiplied by the rate of travel at the general distance of the stations gives the difference in distance of the stations from the epicenter, or DE. Now if arcs are swung from nearby stations using radii AE and CB, the point of intersection will lie on the line desired. By increasing or decreasing the radii like amounts as shown in the Figure, the desired line may be located by swinging arcs using the stations (A and C) as centers. From the Figure it will be noted that these median lines may be determined with sufficient accuracy for distant stations by the use of intersecting perpendiculars which would deviate very little from arcs. For the nearer stations, arcs would be necessary. The results obtained in the case of the Long Beach shock agreed reasonably well with the results obtained at the Seismological Laboratory in Pasadena, differing by approximately 5 miles in latitude and longitude. The data were plotted using computed distances from the Pasadena epicenter which gave the results shown in Figure 11. Note the tendency to a bending of the curve at the shortest distance. This, however, is not so apparent when plotted on a larger scale. The curve was purposely offset in this Figure so plotted points would not be obscured.

The conclusions which may be drawn from this discussion are: First, for best results all instrumental data should be based on absolute time, as there is a decided weakness if one is forced to use relative time in the form of (S-P) data; stations should therefore bend every effort toward making frequent absolute time-comparisons in order to enhance the value of the data which they furnish. Second, in using the data furnished, great care must be used to overcome inaccuracies due to lack of precision in the globes and maps used, thus increasing the chances that the results will truly represent the facts. Concerning this latter conclusion, I will say that the Section of Seismology of the Coast and Geodetic Survey believes the 30-inch globe in use there is fairly accurate since computed arc-distances seldom differ from the measured distances by more than 25 kilometers, the average difference being very much smaller.

U. S. Coast and Geodetic Survey,
Washington, D. C.

STRONG-MOTION SEISMOGRAPH EQUIPMENT AND INSTALLATIONS

H. E. McComb

Two years ago the Coast and Geodetic Survey was authorized to carry out investigations of strong seismic motion. As investigations of this nature had not been com-

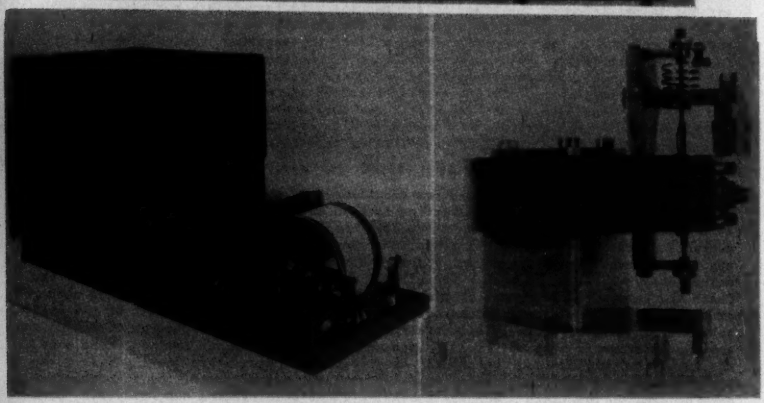


Fig. 1--Three-component accelerograph for photographic registration--automatic starting-recorder, timing-clock, intermittent and permanent stopping-mechanism, three-component Wenner accelerometer, and signal-device circuits

Fig. 2--Plan view of accelerograph (center)

Fig. 3--View of accelerograph showing sectional hinged cover, pendulum starting-device, and portion of tape-attachment using 200-inch long photographic sheets (lower left)

Fig. 4--Horizontal-component Wenner accelerometer equipped with pivot-and-helical-spring suspension-systems

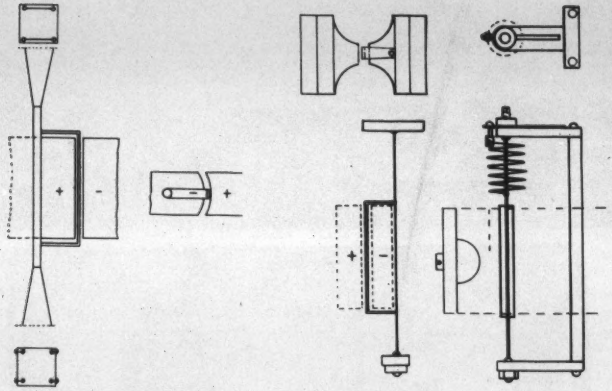


Fig. 5--Schematic diagram showing quadrifilar suspension used on first models of Wenner accelerometers (left)

Fig. 6--Schematic diagram of pivot-and-spring suspension used on later models of Wenner accelerometers

ducted in this country on a comprehensive scale and as suitable instrumental equipment was not in existence at the time, it was necessary to formulate a working program without delay. Such a program included the distribution of development-work to other governmental bureaus and to institutions willing to cooperate in such a program; testing of experimental devices; alteration and retesting of same until performance was reasonably satisfactory; preparation of plans, specifications, etc., for instruments and equipment on a quantity basis; selection and preparation of sites in a seismic region; inspection and testing of all new equipment at factories or in Washington; transportation of all equipment to the field; installation of instruments in widely separated localities in the field; and finally the training of personnel in certain details of operation.

The development of accelerometers and tiltmeters used in the program was carried out at the Bureau of Standards, starting devices and very short-period accelerometers at the Massachusetts Institute of Technology, mechanical recording strong-motion seismographs at the University of Virginia, motor-driven and clock-driven automatic recorders, displacement-meters, pendulum starting-devices, experimental accelerometers, and miscellaneous necessary adjuncts for all equipment by the Instrument Division of the Coast and Geodetic Survey, and at places of manufacture. As a result of this cooperation of the various agencies interested in the program, and as a result of the application of intense pressure by all concerned in order to keep the program in motion and get the instruments into the field as soon as possible, good progress has been made in the direction outlined and intended in the original program. Practically all of the equipment has been shipped to the field, and all but one or two of the instruments manufactured on the first order are installed in seismic regions and ready for operation. Sites have been selected and are now being prepared for the balance of the instruments. All will be installed and ready for operation within a few weeks.

During the recent disturbance in southern California, records were obtained from accelerographs at three stations. These records will be shown and discussed in later papers to be given on this program, but it is believed that it will be well to discuss very briefly at this time two of the instrumental lessons to be learned from these records. They are: (a) The paper-speed, while it is almost double the maximum recommended when the instruments were being designed, should be greater; steps have been taken to provide necessary reduction-gears to double the present paper speed; (b) the contact-accelerometers, while they are satisfactory at sites free from local artificial

Fig. 7--Pendulum starting-device equipped with platinum-cone and platinum-ring contacts and designed for oil-damping (left)

Fig. 8--Weed strong-motion seismograph designed for mechanical registration of two horizontal components and equipped with oil-damping, automatic starting- and stopping-mechanism, and signal-device (upper right)

Fig. 9--Strong-motion seismograph (low-magnification displacement-meter) designed for photographic registration of two horizontal components [Equipped with automatic starting- and stopping-mechanisms, timing-clock, and oil-damping]

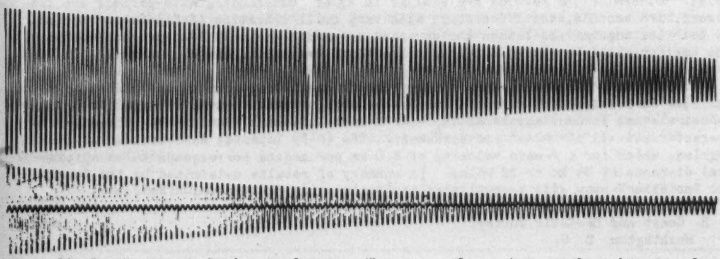


Fig. 10--Decay-curves showing performance Wenner accelerometers, undamped; upper from quadrifilar suspension-system and lower from pivot-and-spring suspension-system

disturbances, are being replaced when necessary by critically damped pendulum-devices having natural periods of about one second.

In closing it should be emphasized that perfection in instruments and records should not be expected under the high-pressure program which has been carried out with such limited personnel. Had there been serious delay or lack of cooperation at any stage of the program, we would not at this time be able to exhibit the records of strong seismic motion recently recorded, and to learn valuable lessons from their interpretation.

U. S. Coast and Geodetic Survey, Washington, D. C.

THE INTERPRETATION OF INSTRUMENTAL RECORDS OBTAINED WITHIN THE DESTRUCTIVE AREAS OF EARTHQUAKES

Frank Wenner

This paper will be published in full in Gerlands Beiträge zur Geophysik.

THE STRONG-MOTION RECORDS OF THE SOUTHERN CALIFORNIA EARTHQUAKE OF MARCH 10, 1933

Frank Neumann

(Abstract)

The shock of March 10, 1933, which caused considerable destruction of property and loss of life in the region immediately south of Los Angeles was recorded at three strong-motion stations of the Coast and Geodetic Survey equipped primarily to record the acceleration in the central region of an earthquake. Accelerograph-records were obtained at Long Beach, Vernon, and Los Angeles, which are respectively 17, 33, and 37 miles from the epicenter. These stations were equipped with Wenner accelerometers, McComb-Parkhurst automatic recorders, and Braunlich starting-devices, except at Los Angeles, where a simple pendulum-starter was under test.

At Long Beach the outstanding feature of the vertical-motion record is the presence of pronounced vibrations of 0.1-second period which must be associated with extremely small amplitudes. The short-period vibrations were superimposed on longer waves of 1.5-second period. The violent part of the shock extended nearly 8 seconds. At Vernon the short-period vibrations having a dominant period of slightly less than one-quarter second are not so pronounced as at Long Beach. Other outstanding periods are 2.5 and 1.5 seconds. The highest accelerations occurred during the first few seconds when there were two waves of about three-quarters second period.

The records obtained at Vernon and Los Angeles, which are only about four miles apart, are generally of the same character except that the large movements observed during the first few seconds at Vernon are missing on the Los Angeles record. Also the high acceleration, long-period waves recorded at Vernon are missing at Los Angeles. Otherwise the records are similar in type. Outstanding wave-periods are 1.5 second, 2.5 seconds, and 0.6 second, with very small vibration of 0.1-second period. At both Los Angeles and Vernon the vertical movements are much less pronounced than the horizontals, whereas at Long Beach the three components are about equal.

It appears that close study of the records may reveal some of the phases so familiar in teleseismic records. One of the most prominent waves recorded at Los Angeles, also at Vernon, may be an "S_n"- or $\bar{S}$-wave. At both stations the directional characteristic is northeast and southwest. The (S-P) interval is 7 seconds at Los Angeles, which for a P-wave velocity of 6.0 km per second corresponds to an epicentral distance of 58 km or 36 miles. [A summary of results determined by the Coast and Geodetic Survey will be published in "Engineering News-Record" for June.]

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE LONG BEACH EARTHQUAKE OF MARCH 10, 1933, AND ITS EFFECT ON INDUSTRIAL STRUCTURES

A. C. Chick*

The Long Beach earthquake occurred Friday, March 10, 1933, at $5^h\ 54^m\ 08^s$ p.m. Pacific Standard Time ($1^h\ 54^m\ 08^s$ Greenwich Time, March 11, 1933), and had its origin, as computed from the time of arrival of the principal wave-phases at seismograph stations, on a fault in San Pedro Bay and located about three and one-half miles off the coast from Newport Beach, in north latitude 33° 34.5 and west longitude 117° 59' (Fig. 1).

The origin was undoubtedly located on either the Inglewood fault extending into San Pedro Bay, or a branch of this fault. The fault-zone in San Pedro Bay has been the active focus for numerous disturbances and has heretofore been called the San Pedro Submarine Fault-Zone, but this is the first damaging earthquake for which the origin has been definitely located in this bay region.

Vigorous earth-shaking lasted possibly 30 seconds or more, and it appears that areas to the north of Newport Beach were more seriously affected than those located nearer the point of origin. In this respect this earthquake is somewhat like the San Francisco shock of April 18, 1906. The first major shocks did most of the damage, although the many after-shocks increased the damage in many instances.

The area within which greatest damage was done to structures, comprises the old flood-plain of the Los Angeles river with deep old deposits of gravels and alluvium with an overlay of more recent similar materials. The ground around Compton, Clearwater, Huntington Park, and Watts, where the most severe shaking appears to have occurred, is for the most part located in a flood-plain of ill-sorted mixture of gravels and alluvium with many marshy spots. Experience in past earthquakes has indicated that it would be difficult to find natural ground less suitable for supporting structures from the viewpoint of their resisting destructive earthquake-motions.

The strength and magnitude of this earthquake, as far as its effect on buildings would indicate, possibly were nearly as great as for the Santa Barbara earthquake of June 29, 1925, although it is understood that instrumental records indicate that the total energy released was perhaps somewhat less than in the Santa Barbara shock, but the area affected is much more densely populated than that about Santa Barbara. This was borne out by the fact that X-cracks did not develop in brick and concrete filler walls in similar types of construction to such an extent as at Santa Barbara.

The fault-movement probably did not cut the surface of the Earth, due no doubt to the absorption of any appreciable movement by the great depth of fill above bedrock, but there were numerous instances, especially in the area of made-land, where the ground showed minor surface cracks (Fig. 2). The direction of these cracks was as frequently east-west as north-south, indicating they had no relation to the underlying fault, but were due to the shaking and settlement of the unstable earth-fill.

Severe earth-shaking was felt from San Diego to Santa Barbara and eastward to a distance of at least 50 miles. Earthquake-waves were transmitted through the water to ships off the coast and, as explained by the Chief Engineer of the Yale, which had left Los Angeles harbor only 54 minutes before the quake, produced tremors in the vessel very much the same as are produced when a propeller is lost from the drive-shaft, except that the effects from the earthquake were somewhat intermittent. This boat travels at a speed of about 23 knots and must have been nearly 35 miles away from the origin of the shock and about 20 miles directly west from the fault-line when the tremors were felt.

The fact that no serious tidal wave occurred along the coast, even though the origin was under the sea, possibly indicates that this quake was not a major disturbance.

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Fig. 1--Area of principal damage (shading shows approximate area in which the principal damage was done)

Fig. 2--Typical surface crack, 1 to 2 inches wide and about 40 feet long, in made-land at Long Beach

Damage to structures was chiefly confined within a radius of about 25 miles from the center of maximum disturbance, although damage was seldom serious at any distance greater than about five miles from the projected fault-line.

Preliminary estimates place the maximum intensity of this earthquake at about VIII to IX on the Rossi-Forel Scale. In the center of the city of Los Angeles the intensity probably did not exceed intensity VI, or at most VII.

This shock was recorded by three of the newly developed strong-motion accelerographs designed by the United States Coast and Geodetic Survey. One of these was located in Long Beach, near the center of disturbance, one in the Vernon industrial section (in the Central Manufacturing District Terminal Warehouse), and one in the business district of the City of Los Angeles. The records, although somewhat confused because the various components (north-south, east-west, and vertical) overlapped each other, nevertheless are expected to give considerable valuable information as to the possible accelerations of the earthquake-vibrations. The scientists of the Coast and Geodetic Survey in Washington are analyzing the records to obtain a reasonable interpretation. As the first returns in an effort to collect information of value to the structural engineer,

these instruments and their records may be considered as marking the advent of a new era in the study of earthquakes.

There have been a great many aftershocks, several hundred in number, and some quite strong. They do not all come from the same point in the fault, but generally they come from points not very far distant from the focus of the original shock.

These aftershocks are still occurring, two months after the main shock, but they have decreased in frequency somewhat sooner than in some of the more violent earthquakes that have occurred in the Pacific Coast Region.

Professor R. R. Martel of the Department of Structural Engineering at California Institute of Technology assembled several instruments which he has placed in the basements and upper stories of a few representative buildings in Long Beach, and has obtained records of the motions produced by these aftershocks. From these records Professor Martel is hopeful of learning considerable about the transmission of earthquake-vibrations through buildings.

The effect of the earthquake on structures

This study has been confined chiefly to the effect of the earthquake on industrial buildings, and was made for the Manufacturers Mutual Fire Insurance Company of Providence, Rhode Island.

In general, the damage to such buildings presents few new lessons but quite emphatically shows the results of faulty design and workmanship as well as the inherent structural weaknesses that are present in the various types of construction that are met with in a warm climate not subject to destructive natural elements such as strong winds, heavy rains, and freezing weather.

Thus in a community that has had such abnormal growth as Los Angeles and the neighboring cities and towns, it is not surprising that the municipal building-codes should be deficient in requirements that might have lessened the extent, if it would not have prevented practically all, of the damage except for customary and expected cracks in tile-walls and plastered partitions. It is not surprising when one realizes that the Los Angeles building-code permits the erection of limit-height buildings, not over 150 feet, without specific wind-bracing, that a great many of the buildings in that City suffered cracks in interior tile-walls and plastered partitions and the flaking off of terra-cotta wall-facings to a greater or less degree, even though the earthquake-motion in that area was not very severe. The total damage in Los Angeles has been estimated as probably not exceeding $1,000,000, while the total damage in all affected areas has been estimated between $50,000,000 and $75,000,000.

The new Edison Building, at the corner of Fifth Street and Grand Avenue, a steel-framed reinforced-concrete office building, understood to have been designed and built under the supervision of Professor R. R. Martel to withstand a horizontal force whose acceleration might be one-tenth that due to gravity, had no damage whatsoever (Fig. 3). This building is about 11 stories in height and has a well-braced steel frame which was riveted for vertical load and electrically welded for horizontal stress.

The Los Angeles City Hall with its tower rising to a height of some 470 feet above the sidewalk suffered extensive cracks in interior tile-partitions and plaster above the tenth story and considerable less-serious cracking of walls and plaster in the lower stories (Fig. 4). It is estimated that repairs will amount to about $35,000.

In Long Beach, well-designed and well-built tall office buildings of both steel-frame and reinforced-concrete construction, ranging in height up to 15 stories, behaved very satisfactorily when it is considered that few, if any, special precautions had been taken to resist a horizontal earthquake-force. The damage was typical of that which has occurred during earthquakes in other cities. There were relatively few buildings of this class in Long Beach, and the damage consisted chiefly of cracked filler-walls and interior plastered partitions. However, in structures where the design and the quality of the materials and workmanship were questionable, quite extensive damage has been found.

Fig. 3--Edison Building, Los Angeles

Fig. 4--Los Angeles City Hall

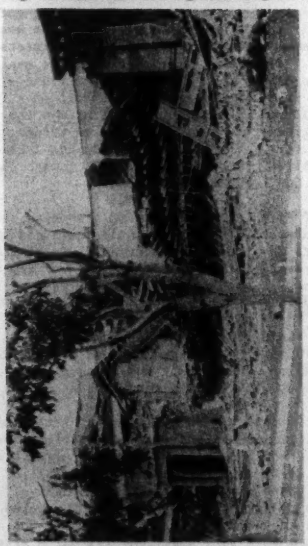


Fig. 6--Typical damage, Jefferson Junior High School, Long Beach

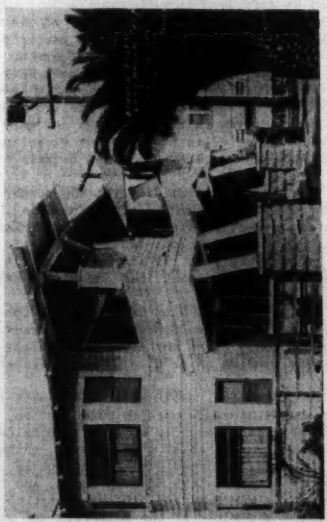


Fig. 5--Typical damage, wood-frame house moved off foundation, and dropped to ground

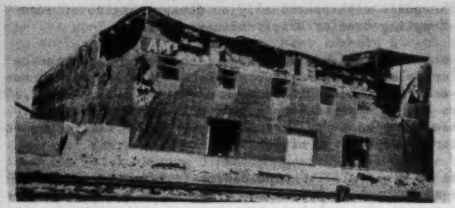


Fig. 7

Fig. 8

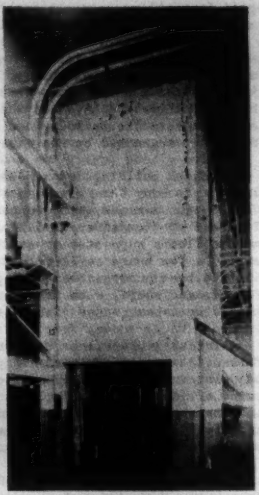


Fig. 10

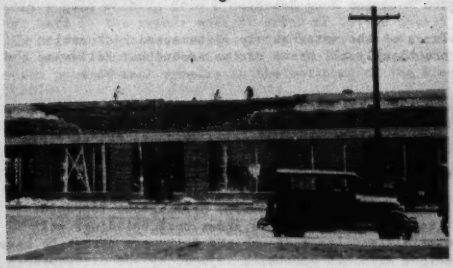
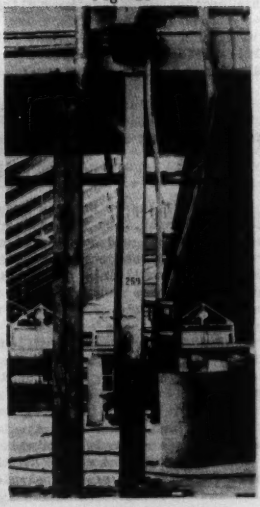


Fig. 12



Figs. 7-12--See text for descriptions

Wood-frame buildings, especially homes of the one-story bungalow type, set on good foundations, came through the quake with practically no damage outside of some cracked plaster and the general toppling over of brick chimneys.

There was a considerable number of these homes, however, that were supported on short vertical wood struts, or "cripples," from one foot to 2.5 feet tall, placed between the sill and the basement-wall (Fig. 5). It has been estimated that about 2,100 homes of this type have had these short supports topple over with more or less serious damage as the building has been dropped to the ground. Some of the damage was undoubtedly augmented by the disastrous work of termites.

School buildings appeared to be especially susceptible to severe damage. The 85 schools in Long Beach, valued at approximately $50,000,000, have been estimated to be 75 per cent damaged, many to the degree of complete collapse as shown by the view in Figure 6 of the Jefferson Junior High School of brick bearing-wall construction with wooden floors supported on wooden floor-joists of long spans. Had the earthquake occurred a few hours earlier, when these schools were in session, there would undoubtedly have been hundreds and perhaps thousands of children killed by falling walls, floors, and roofs, with the result that this earthquake would have ranked as one of the major catastrophes of this era.

Investigations into the construction of many of the collapsed school buildings have failed to place the blame on any particular persons or groups, but they have served to point out the absurdly poor construction which was the major contribution to the cause of destruction. The outcome of these investigations will without doubt result in more strict building-codes and provisions for earthquake-resisting designs particularly for all public buildings in this and other recognized active seismic regions on the Pacific Coast.

There were very few fires following the earthquakes, and the total damage from this source is estimated at about $2,000,000. Most of this loss was suffered by the high-school buildings in Huntington Park and Long Beach.

There were no important failures of the water-supply systems, and restoration of this protection was complete in practically all areas on the second day following the shock.

All supplies of electric current and gas were shut off by the Public Utilities Companies in about five minutes after the first severe temblor, and these acts of foresightedness undoubtedly contributed in a large measure to the scarcity of fires.

Damage to industrial buildings and structures

A brief survey of many industrial plants in Long Beach, Wilmington, Torrance, Compton, Vernon, and the southern section of Los Angeles shows that buildings well constructed of good quality of materials and large enough and fortunate enough to have received competent engineering design, were not seriously injured by the earthquake. Many smaller buildings of ordinary type of construction built apparently without much consideration as to design, but with good materials and good workmanship, generally were not seriously damaged.

Poor construction, typified by inadequate ties between walls, roofs, and floors, and by the use of inferior materials and poor workmanship, very generally suffered severe damage ranging from toppled parapet-walls to complete collapse in some instances.

It is understood that the Los Angeles section of the American Society of Civil Engineers has recently appointed a committee, headed by R. R. Martel, which will make a thorough study and report on the structural damage and the ability of various types of construction to resist seismic forces.

(1) Bearing-wall structures--These are generally of brick-wall construction with or without pilasters, having wooden roofs and floors with supporting beams bearing directly upon the walls and mostly without adequate anchors for holding the walls in place. The interior loads are carried on wooden or steel columns. Foundations are usually the common type of concrete-footing.

In buildings of this type, damage consisted mostly of overturned parapets and cracked brick-walls, although in some cases portions of walls were toppled over, allowing the roof and floors to drop. This is shown by the view in Figure 7 of the American Wholesale Hardware Building, West Anaheim Street at Nadeau Street, Long Beach--a 3-story, heavy-joisted, brick bearing-wall building; here poorly bonded brick-work was seriously damaged with cracks extending to foundation; falling roof fractured sprinkler piping, causing serious water-damage to contents; no window-glass was broken, indicating that horizontal sway was limited in amount. There are many examples of strongly built masonry walls that survived with little or no damage. The extent of damage is measured to a great degree by the quality of the mortar and workmanship, as is evidenced in Figure 8, which shows typical damage to a one-story, poorly built brick bearing-wall structure on East 16th Street at American Street, Long Beach. In no buildings of this type do we find any diagonal bracing, and almost without exception the fundamental requirement that, for earthquake-resistance, elements of a structure must be securely tied together so that all will act as a unit, has been violated. Interior partitions of tile or brick are found badly cracked.

The excellent quality of materials and workmanship sometimes found in buildings emphasizes the inferior quality of materials and the careless work found in small structures, especially those erected by speculative builders. Tests have been made indicating that, in some cases, mortar with only about one part cement to 20 parts of lime-mortar have been used. Joints have been tested in many cases with a knife and some have been found of inferior quality, where the mortar could be very easily powdered in one's hand. Walls that have been damaged show little cracking of the bricks themselves--the cracks usually follow the mortar joints. Obviously, brick laid with this kind of material cannot be expected to stand against a severe earthquake, or to transmit the horizontal forces throughout the wall as a monolithic mass. In falling, brick walls have generally been broken up into small units of individual bricks.

Repairs are being made with little or no thought of increasing the resistance to earthquake-forces. Parapets are being replaced using the same bricks that often needed only a good washing from a hose stream to clean off the old mortar. However, the mortar used in the repair work is often of better quality and when the next severe shaking occurs the person on the sidewalk may expect to be crushed with a sizable slab of brick-work instead of being hit on the head or shoulders by a single brick. Figure 9 shows parapet-wall repairs to the building of the Brown-Bevis Company at Vernon, California.

(2) Steel-framed structures--Steel-framed buildings with corrugated iron or asbestos-covered roofs on steel trusses, and corrugated iron or asbestos-covered walls, with ordinary wind-bracing by means of vertical and horizontal diagonal rods designed to resist a wind-pressure of probably not more than 15 pounds per square inch, have no damage worth mentioning, outside of some cracked plaster, tile, and brick-work of interior walls and partitions. Such a case is shown by Figure 10 giving an interior view of the assembly-room of the Ford Plant at Long Beach. Here slight damage was confined to cracked elevator-enclosure, cracked plaster in office, and cracked interior-wall of boiler-room. This is a steel-frame building with brick walls and corrugated asbestos roof. Diagonal wind-bracing aided in minimizing damage.

Steel-framed buildings with well-laid brick walls have developed typical X-cracks in the filler-walls and more or less shattering of the brick-work at the steel wall-columns. Where diagonal rods have been used for wind-bracing and where the brick-work has been exceptionally good, the damage is very slight. In no case was a building of this description found in the state of total or even partial collapse.

Steel-framed buildings with good concrete-walls and floors and nominally good wind bracing suffered slight damage in most cases, consisting chiefly of cracked curtain-walls, spandrels, and fire-proofing, and in some instances deformed steel columns. There were exceptions, however, as in the case of a large manufacturing plant, where damage was quite extensive, but here there was noticeably inadequate bracing of the structural steel-frame which carried heavy floor-loads and a heavy roof of reinforced concrete. In this plant the damage comprised: (a) Deformed steel columns and other structural members of the high one-story buildings carrying a heavy saw-tooth roof of concrete (a typical example of an unbraced column supporting a heavy roof of concrete, deformed when subjected to bending, is shown by Fig. 11); (b) shattered concrete-fireproofing; (c) fractured interior concrete-walls, especially

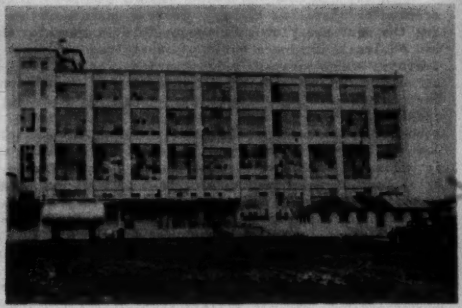
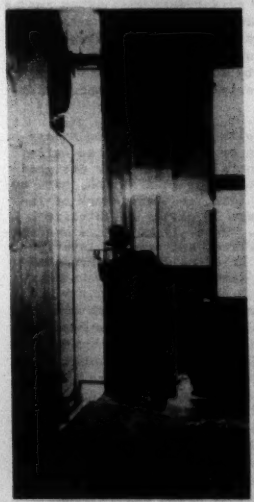
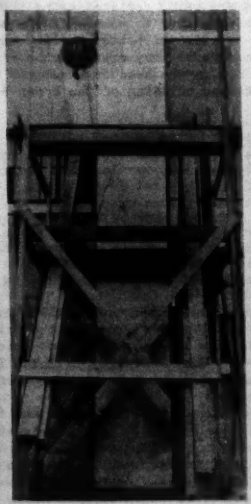


Fig. 14--Reinforced-concrete steel-frame building; reinforced-concrete stairways were severely damaged, also a few wall-columns were fractured; rivets were sheared off at one joint of steel corner column and steel wall-beam (note the large amount of broken window glass)

Fig. 15--A typical fracture of interior reinforced-concrete walls, without diagonal bracing, enclosing elevator





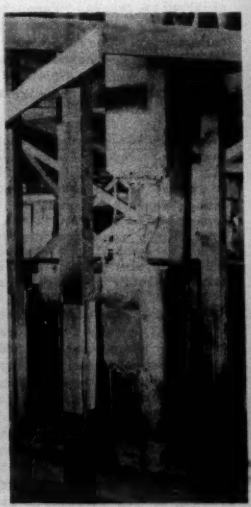


Fig. 16--Light space shows opening between outer wall of 4-story building at left and 3-story building which formerly abutted (6-inch rule held by man)

Fig. 16--Typical diagonal crack, 1st-story reinforced-concrete wall-column of 2-story reinforced-concrete building; interior of mushroom-type construction practically uninjured although reinforced saw-tooth roof had some vertical concrete-members fractured

Fig. 17--Inadequate concrete-columns of building in central manufacturing district, Vernon

Fig. 18

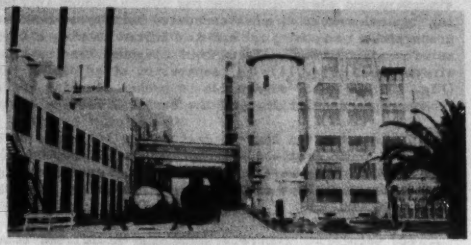


Fig. 19--Procter and Gamble plant, Long Beach

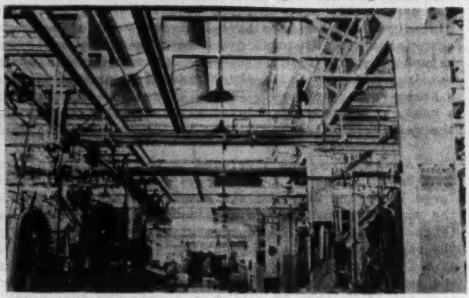


Fig. 21--Steel framework aids in resisting quake

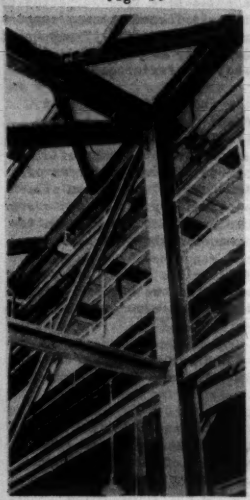


Fig. 20

Fig. 22

Fig. 18--Outside wall-column of building in Figure 17 showing fractured concrete-column while brick-work remains uninjured although brick walls in other part of building showed some cracks

Fig. 20--Process Building of Procter and Gamble, showing steel frame with vertical and horizontal bracing

Fig. 22--Morgan Motor Company, American Avenue at East 16th Street, Long Beach, California (a well-built reinforced-concrete building suffered slight injury while an adjoining building of poorly bonded brick-work was completely demolished)

stairways and elevator-enclosures such as shown in Figures 12 and 13--the first showing typical cracks in plaster-coated reinforced-concrete walls (cracks cleaned out preparatory to repairing) and the latter showing a typical fracture of interior reinforced-concrete walls without diagonal bracing and enclosing elevator; (d) broken window-glass (Fig. 14); (e) separation of adjoining buildings of different heights (Fig. 15); (f) roof damage due to broken flashing and split roof covering, and (g) broken pipes and fittings of the vertical feeders of the sprinkler-system.

It is estimated that to restore the buildings of this plant to their original condition would cost about $1,000,000 to $1,250,000, whereas repairs sufficient to make the buildings safe for operation and providing additional bracing to give greater resistance against any future earthquake are expected to be made for a total of about $200,000.

(3) Reinforced-concrete buildings--Reinforced-concrete buildings came through the earthquake remarkably well in all cases where the design was good and the materials and workmanship were of first quality. Poor concrete and insufficient and improperly placed reinforcing bars have been responsible for most of the damage, which in general comprises: (a) Diagonal cracking of concrete-walls and spandrels, mostly of a minor nature (Fig. 16); (b) fracturing of concrete-columns when these have been subjected to bending, and especially where undersized and insufficiently reinforced columns support a heavy roof of concrete (Figs. 17 and 18--the third-story column of Fig. 17 supported a heavy concrete-roof which could not withstand bending caused by earthquake-forces, the reinforcing being entirely inadequate, and the concrete of inferior quality).

A revelation was disclosed in the plant of the Procter and Gamble Company at Long Beach. This is a reinforced concrete, partly steel-frame plant comprising two large buildings five and six stories high designed to resist earthquake-forces, where the structural damage was confined to bridges and tunnel connecting the two buildings (Figs. 19 and 20). It is located on filled land very close to the supposed line of the earthquake-fault. The buildings are supported on a concrete-mat on wooden piles 42.5 feet long, driven to refusal. These buildings were designed by Stone and Webster and built under their supervision. The design included the provision that the buildings should be able to resist an earthquake-force with an acceleration equal to one-tenth that due to gravity.

The only real structural damage suffered was confined to the two bridges and the underground concrete-tunnel connecting the two main buildings--these were pulled loose at one end.

The Earth around the plant settled from 1 to 6 inches and several cracks 1 to 2 inches wide and from 15 feet to 40 feet long appeared in the surface. Small sand craterlets were also created.

In the face of adverse location near the fault and on made-land, the fact that these buildings resisted the earthquake-forces without any serious structural damage is additional indication that it is possible to build structures of reinforced concrete, on the most unstable ground, that will successfully withstand even the most severe earthquake we may expect in this country.

At the plant of the American Can Company in Vernon, the effect of rigidity of a structure in resisting motion was very apparent. This is a reinforced-concrete plant. In one section of a one-story building with a heavy saw-tooth roof of concrete there was practically no damage, due undoubtedly to the fact that the structure was thoroughly tied together by steel framework supporting interior conveyors and shafting. Such a case is shown by Figure 21 of a section of a reinforced-concrete can factory at Vernon which suffered little structural damage because it had interior steel framework supporting conveyors and shafting which helped to hold the building in shape; another similar section without such steel-work had some exterior wall-columns cracked and some vertical saw-tooth members fractured. Another similar portion of the plant without such steel framework suffered damage in the form of cracked wall-columns and some fractured vertical concrete saw-tooth roof-members.

An interesting comparison of the effectiveness of reinforced concrete as compared with poorly bonded brick-work in resisting earthquake-forces is offered by the build-

ings of the Morgan Motor Company on American Avenue at East 16th Street, Long Beach, California (Fig. 22). The brick walls supported a wooden Summerbell truss-roof. This portion of the building was in a state of almost complete collapse, while the reinforced-concrete portion remains in use with minor injury consisting chiefly of a few cracked wall-columns.

A survey of the damage caused by this earthquake emphasizes other features from the study of which we can draw important conclusions.

(4) Interior partitions--Interior partitions of tile or brick masonry will almost always be seriously damaged in a severe earthquake unless the building is constructed with sufficient rigidity and strength so that the frame will absorb most of the lateral force without transmitting it to these non-elastic members.

Metal-lath and cement-plaster partitions have much more flexibility and damage will generally be confined to cracks that can readily and inexpensively be repaired.

(5) Elevated water-tanks on steel-towers--A few elevated water-tanks on steel-towers were thrown down when their supporting structures failed, but for the most part such structures, where adequate wind-bracing was used, were not damaged beyond the loosening and occasional breaking of diagonal guy-rods, although it is quite evident that many of these structures were stressed nearly to the point of failure. The greatest injury almost invariably occurred in the top-section of the tower. In two out of three cases investigated, where diagonal rods were broken, the break occurred at an old flaw in the metal.

A few towers were slightly twisted but not seriously.

There were several instances of the failure of concrete-framed supports for water-tanks on roofs of buildings. Such supports were undoubtedly designed for vertical load plus wind-load only. Under the much greater horizontal force of the earthquake the concrete-columns were subjected to bending for which they were not designed, and consequently these columns were fractured. In a more severe earthquake or one of longer duration these supports would undoubtedly have failed entirely, letting the heavy tank of water crash down through the roof and floors below with considerable structural damage and possible loss of life.

(6) Damage to sprinkler-systems--Heretofore, the ever-present liability of extensive sprinkler leakage-losses from the rupture of the sprinkler-piping in buildings due to earthquake-causes has received little or no consideration. This is a hazard present in nearly all plants on the Pacific Coast to a much greater degree than in most other parts of the country. This is not only true on account of the greater frequency of severe earthquakes but also because many of the buildings because of the mild climate are much inferior in design and quality of workmanship.

In several plants the sprinkler-pipes have been found either cracked or fractured at the fittings, and in some buildings considerably bent out of shape where they have extended through tile-walls that have been toppled over. Moreover, in rigid concrete-buildings the experience in this earthquake showed that there is the liability of the risers being sheared off or broken.

In this connection there is also to be considered the personal element of the watchman or engineer who will refrain from entering a damaged building after an earthquake to shut off the water-supply.

(7) Damage to machinery and contents of buildings--Damage to contents due to breakage will depend not only upon the materials comprising raw-stock and finished products, but also upon the manner of storing or piling. In a region subject to severe earthquake shocks it is well to give this matter serious attention and a good insurance-underwriter will make careful study before granting such coverage.

Possible damage to machinery has not heretofore received due consideration in estimating the probable amount of loss that an industrial plant may suffer. Breakage will play a small part unless the building collapses, but injury from misalignment may present a serious loss. Certain types of machines, of course, are much more subject to this kind of damage than others.

In the case of one plant, the Chief Engineer advises that realignment of the machinery cost about $25,000.

(8) Adjustment of earthquake insurance-losses--The adjustment of losses caused by earthquake-damage to structures and to contents and machinery may present a difficult problem, because of the uncertainty as to the amount of cracking of walls and plaster due to shrinkage and settlement of foundations, also the difficulty of estimating the condition of machinery prior to the earthquake.

For this reason it is suggested that every insurance policy should contain a Percentage Deductible Clause, which would exclude a small amount from payment for damage, equal to not more than 1/2 or 1 per cent of the sound value of the property insured. This provision would prevent much disagreement in settling losses and at the same time would not place any hardships upon the assured.

Conclusions

To summarize, the experience of this earthquake substantiates the lessons learned from previous earthquakes and justifies the conclusion that industrial buildings of good design, good materials, and good workmanship may be relied upon to resist the most severe earthquake we may expect in this country, with little serious structural damage. At plants where either one of these elements is lacking there will be more or less damage, but generally poor construction has been the greatest factor in producing the large amount of damage in this and most other earthquakes.

Certain specific principles emphasized by this earthquake may be summarized as follows:

(1) As far as possible, a building should have adequate bracing to cause the structure to act as a single unit.
(2) Adequate horizontal bracing should be provided for large, heavy roofs, even on low buildings. Light roof-construction is advisable for large areas.
(3) Good cement-mortar should be used for brick-work and brick-walls should be securely anchored to floors, roofs, or structural frames.
(4) Unanchored high parapet-walls, heavy cornices, and ornate trim should be avoided.
(5) A space should be left around fire-protection piping where it passes through foundations, walls, floors, or roofs.
(6) Outside control-valves should be provided on all gas, electric, and water feed-mains so that broken mains or wires can be shut off without having to enter the building.
(7) Gravity water-tank towers in earthquake-areas should be designed with supporting columns and diagonal bracing adequate to resist earthquake forces.

Manufacturers Mutual Fire Insurance Company,
Providence, Rhode Island

PRECISE GEODETIC MEASUREMENTS AND THEIR RELATION TO SEISMOLOGICAL INVESTIGATIONS

William Bowie

The use of precise measurements is becoming more general in efforts to interpret the phenomena connected with changes in the Earth's surface. It may be that the use of these precise measurements will eventually lead to a more exact knowledge as to how the Earth's surface originally became so irregular with great areas standing high, as continents, and other areas depressed, as ocean basins.

The science of seismology is adding much to our exact data. The locations of the epicenters of earthquakes and the determination of their intensity and the rate of transmission of the earthquake-shocks through the Earth's materials at different depths furnish information of the highest value.

The geodetic measurements in the form of triangulation and leveling are brought into the picture, for by their means one is able to determine the magnitude of earth-

movement during an earthquake on land and the extent of the strains in the Earth's crust in given regions between earthquakes.

The Federal triangulation- and leveling-nets being extended over the United States by the United States Coast and Geodetic Survey call for first- and second-order triangulation and leveling with arcs and lines spaced at intervals of about 50 miles. Presumably the first-order work will be spaced at intervals of 100 miles with the intermediate areas controlled by second-order work. Even second-order triangulation and leveling are very high grade and enable one to determine with considerable accuracy any earth-movements that may occur in the immediate vicinity of such triangulation and leveling.

There is an increased interest in triangulation and leveling in this country, for it is realized by engineers and others that these two classes of surveying furnish data that can be used in many classes of engineering--in topographic mapping and in the establishment and perpetuation of private and public property-lines. With this increased interest in triangulation and leveling it is reasonably certain that the spacing of the arcs and lines will be reduced to 25 miles. With such spacing very few places in the country will eventually be more than 12.5 miles from a triangulation-station or a leveling bench-mark.

There are now in this country 37,000 miles of arcs of triangulation and about 76,000 miles of leveling, most of which is of the first-order. At the present rate of progress the 50-mile spacing of arcs and lines can be completed within eight years.

All of this triangulation and leveling can be used for determining the extent of earth-movement during earthquakes. The first-order triangulation of California that had been completed prior to 1906 was repeated in later years to show what movements had taken place in the triangulation-stations that were close to the San Andreas Fault. A report on this work is contained in Special Publication No. 151 issued by the United States Coast and Geodetic Survey.

Beginning in 1922, the United States Coast and Geodetic Survey cooperated with the members of the Advisory Committee in Seismology of the Carnegie Institution of Washington. It was through the efforts of that Committee that Congress made an appriation especially for carrying on geodetic work in regions suspected of seismic activity. At first the funds available were used for extending an arc from western Nevada southwestward to San Francisco Bay, thence southward to the Mexican border, and thence eastward into western Arizona. Then in recent years special arcs of triangulation and lines of levels have been run in what are considered critical areas--from a seismological viewpoint--in California.

The special arcs of triangulation were connected with existing first-order work. The new arcs were each projected across one or more fault-zones where earthquakes had occurred in historic or recent geological times. These arcs consisted of what might be considered a main scheme of triangles with observations of first-order and within it a secondary scheme with the stations spaced fairly close together. The stations were especially close in the immediate vicinity of a fault-zone. In all, six short arcs of detailed triangulation similar to the one just described have been completed. Special lines of levels have been run across certain fault-zones. After an earthquake near these special arcs and lines has occurred, the work will be repeated.

Within the last few years a line of levels has been run in the Imperial Valley after an earthquake had occurred near El Centro. While no great movements of the Earth in the vertical sense were noted along the repeated line, yet there were a few bench-marks located near the fault-zone which showed that actual movement had occurred. The changes of these marks were larger than could be accounted for by the ordinary accidental errors of first-order leveling.

During the past six months lines of levels have been run in three directions from San José. Evidence had been furnished the Coast and Geodetic Survey Office in Washington by local engineers which showed that some changes in the elevations of bench-marks had occurred in the vicinity of San José. The releveling shows conclusively that one of the bench-marks in the immediate vicinity of San José had been depressed as much as four feet. On each of the lines of levels run from that place, one northwest, one southeast, and one north, some of the bench-marks were found to

have undergone subsidence by varying amounts. On each line the leveling was repeated until the new leveling and the old agreed for quite a distance, thus making it possible to determine the limits of the affected area. The decided changes, which must be attributed to earth-movement, extended along the three lines to the following distances from San Jose: On the line northwestward toward San Francisco, 22 miles; on the northward line toward Sacramento, 18 miles; on the line southeastward toward Santa Margarita, 12 miles.

No definite conclusions have yet been arrived at as to the exact cause of the settlement in San José and vicinity. The seismological records do not show that any earthquake has occurred in the affected region since the first leveling was done.

It was brought to the attention of the members of the Advisory Committee in Seismology that earth-movements were occurring in an oil-field in the vicinity of Taft, California. Upon request of this Committee, the Coast and Geodetic Survey made a local triangulation of the region affected in order to establish stations which could be reoccupied within a reasonable time in order to detect, if possible, the rate of movement.

The plans for geodetic work in regions of seismic activity for the fiscal year beginning July, 1933, have not been completed but it seems reasonable to assume that there will be some triangulation and leveling done in Long Beach, California, in order to learn, if possible, the extent of earth-movement during the earthquake of March of this year.

It is very desirable to discover how wide an area is affected during an earthquake. Is it one mile, five, ten, or some other number of miles on each side of the active fault? The only way to determine this is by having lines of levels and arcs of triangulation extend across fault-zones. Repetitions of the field-observations should make it possible to determine the width of the zone that is affected.

With a knowledge of the horizontal extent to which the Earth's surface has moved, we should be able to draw correct conclusions as to whether the cause or causes of earthquakes are local or regional in charcter.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GEOPHYSICS IN 1932

F. W. Lee

It is expected that this article will appear shortly as a publication of the United States Government in more complete form than is possible to publish in the Proceedings.

U. S. Bureau of Mines,
Washington, D. C.

VELOCITIES OF WAVE-TRANSMISSION IN ROCKS

L. H. Adams

(Abstract)

A brief report was given on some of the aspects of the velocities of wave-transmission in various rocks, and especially with regard to laboratory measurements.

The time required for earthquake-waves to travel from one point on the Earth's surface to some other point has been known for a long time, and at an early date it was found possible by mathematical analysis to use these travel-times to calculate the wave-velocities at various depths below the surface. But the kind of rock at the various depths was not known, and hence these early seismological results could not proper-

ly be called measurements of wave-velocities in rocks, because of the unknown character of the material through which the waves passed.

It is well known that these velocities may be calculated exactly from the elastic constants and densities of the rocks. Specifically the velocity of transverse vibrations is obtained from the rigidity and that of the longitudinal vibrations from the rigidity combined with the compressibility. In order to take advantage of this method of determining wave-velocities, many attempts were made to measure the elastic constants in the laboratory. Apparently the first measurements of any consequence were those carried out more than 25 years ago by Frank D. Adams and Ernest G. Coker. The measurements were made by an indirect method, that is, by putting a column of rock under compression in a press and measuring the diminution in length and the increase in cross-section--in other words, determining Young's modulus and Poisson's ratio--and using these results to calculate the rigidity and compressibility. The method was therefore an indirect one, although more successful than the previous indirect methods. Direct methods of measuring these elastic constants were naturally much to be desired, but until about ten years ago no such measurement of any elastic constant of any rock had ever been made. At this time, however, it was found practicable to obtain reliable direct measurements of the cubic compressibilities of various types of rocks. These results were obtained at the Geophysical Laboratory by the use of hydrostatic pressures above 10,000 atmospheres. Although the rigidity was not measured, seismologic data offered us an accurate ratio (for deep-seated rocks) between the rigidity and the bulk modulus, and it therefore became possible to calculate the velocity of longitudinal and transverse waves in all the well-known rock types. It was a source of gratification to find that the value obtained for granite at a depth corresponding to 10 km was 5.6 km/sec, which was precisely the value announced by seismologists as the measured velocity in the outermost, presumably granitic layer of the Earth. This agreement justified the expectation that laboratory measurements could be used to calculate wave-velocities in typical rocks, and thus in conjunction with measured earthquake wave-velocities could afford a clue to the type of rock at different depths through which the elastic waves may have passed.

In the somewhat limited field of indirect measurements on velocities in non-sedimentary rocks, many interesting results have been obtained. Among the more significant ones are (1) that the velocity of longitudinal waves in gabbroic rocks at a pressure corresponding to a depth of 50 kilometers is 7.3 km/sec; (2) that the only well-known rock types that will allow a velocity of 8.0 km/sec or higher are peridotite and eclogite; and (3) that the velocity in metallic iron is less than in any common igneous rock except granite.

Apparently neither field methods on the one hand--methods involving natural or artificial earthquake-waves--nor laboratory methods on the other hand, are alone adequate for determining the wave-velocities in rocks. The two kinds of measurements mutually supplement each other. This is especially the case for rocks at considerable depth. It is to be hoped that more precise seismologic data will be accumulated, that in the laboratory the range of pressures, the range of temperatures, and the variety of quantities measured can be extended, and that many more field measurements of wave-velocities in various rocks can be obtained.

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

A COMPARISON OF LABORATORY AND SEISMOLOGICALLY DETERMINED ELASTIC CONSTANTS OF ROCKS

W. A. Zisman

(Abstract)

Measurements of the elastic constants of rocks were made in the laboratory by static methods using specimens of rock taken from the locality in which Leet and Ewing had measured the elastic constants by seismological methods. It was found that the statical elastic constants, Young's modulus, and Poisson's ratio were always less than

the seismologically determined ones, and that the statical compressibility of the "covered" rock is always far too large. On the other hand, the statically obtained compressibility of the "uncovered" rock is in excellent agreement with the seismic value. These experimental results can be clearly explained qualitatively as due to the presence of cracks and cavities in the rocks between adjacent crystals. This explanation at the same time suggests that the cracks and cavities will cause the rock to behave as an absorbing and dispersing medium for the propagation of elastic waves. At great depths in the Earth the probable disappearance of pores in the rocks will eliminate this behavior of elastic waves.

Harvard University,
Cambridge, Massachusetts

VELOCITY OF ELASTIC WAVES IN GRANITE AND NORITE

L. Don Leet

(Abstract)

The velocities of elastic waves were investigated in granite at Rockport, Massachusetts, and norite at Sudbury, Ontario. The waves measured were generated by dynamite explosions, and recorded by portable seismographs at distances up to 6,260 feet in granite and 10,320 feet in norite. The observed velocities in km/sec with probable errors indicated by ± were as follows: Rockport granite--longitudinal, 5.14 ± .005; transverse, 2.70 ± .02; Rayleigh, 2.19 ± .007. Sudbury norite--longitudinal, 6.22 ± .003; transverse, 3.49 ± .006; Rayleigh, 2.79 ± .01.

From these velocities, and the densities of specimens taken from the shooting-locations, the following elastic constants may be computed. They are shown in Table 1 for comparison with those computed by a similar procedure in an earlier report for Quincy, Massachusetts, granite.

Table 1

Constant	Quincy granite	Rockport granite	Average granite	Sudbury norite
Density	2.61	2.63	2.62	2.85
Rigidity $\times 10^{-11}$, dynes/cm^2	1.63	1.92	1.78	3.47
Bulk modulus $\times 10^{-11}$, dynes/cm^2	4.4	4.4	4.4	6.4
Young's modulus $\times 10^{-11}$, dynes/cm^2	4.3	5.0	4.65	8.82
Compressibility $\times 10^{13}$, cm^2/dyne	22.8	22.8	22.8	15.6
Poisson's ratio	0.33	0.31	0.32	0.27

A quartz-rich zone in the norite was found to transmit the waves with a slower speed.

The results are compared with statical measurements of Zisman on rocks from the same locations, a part of the same program of geophysical research at Harvard. Compressibility, measured directly, under hydrostatic pressures, on specimens exposed to the liquid transmitting the pressure is found to be the only statically determined constant which yields seismically effective values. The geological significance of granite velocities and elastic constants is discussed. It is concluded that a longitudinal-wave speed of 5.5 km/sec cannot be regarded as unique for granite, or even necessarily suggestive of granite, as has been repeatedly proposed; and that there is as yet no seismological justification for the identification of any "layer" of the Earth's crust as either sedimentary or granitic. It is asked whether, so far as the outermost 15 or 20 kilometers are concerned, there is any geological justification for speaking of "layers" of any kind.

Harvard University,
Cambridge, Massachusetts

THE INTERPRETATION OF REFLECTION-SEISMOGRAMS

H. M. Rutherford

It is usually assumed, in the application of seismology to geological exploration, that the Earth's crust is stratified. Each of these strata, within limits, is considered to be isotropic and homogeneous, with a unique and constant velocity. This is merely a working hypothesis, which under favorable conditions gives satisfactory results. In regions where actual conditions closely approximate the ideal, such as finding the thickness of glaciers, rectilinear propagation paths can be used to great advantage (Hans Mothes, Seismische Dickenmessungen von Gletschereis, Zs. Geophysik, v. 3, 121-134, 1927). Also, where the depths of exploration are only of the order of a few hundred feet accurate cross-sections can be drawn. Ideal conditions can often be approximated by the use of a calibrated "average" velocity; this will be discussed in detail later.

An example of what is meant by favorable conditions is the mapping of the surface of the syenite in the vicinity of Bauxite, Arkansas. Here wells have been logged, before they were drilled, to within one foot in a hundred. However, the total depth did not exceed some 300 feet. A factor in these computations was the low velocity of the overburden and the high velocity in the syenite.

Time-distance data obtained in the Gulf Coastal Region, in the exploration for salt-domes, were interpreted upon the basis of three strata. These strata were named, for want of better terms, the "unconsolidated," "semi-consolidated," and the "consolidated." At first the main aim was the detection of salt-domes and this hypothesis sufficed for the purpose. A wave which travels through a salt-dome shows a smaller time of travel, for the same shot-length, than would be obtained in the same region if it were normal. Thus it was relatively easy to detect the presence of salt-domes and the particular theory of the structure of the Earth was not important.

Naturally, it was of great importance to know the depth of a dome or structure. If the structure were shallow, the depth could be obtained to a fair degree of approximation. In the case of deep domes, some of the depths calculated were somewhat phantastic. Also depths to these various "geophysical" horizons did not check with known geological horizons. The author reworked, with E. E. Rosaire, many of the time-distance charts in an effort to find a curve which would best represent the data. It was found, in the Gulf Coast, that a curve of the form $X = (At^2 + Bt)$ would fit the data to a good degree of approximation (M. Ewing and L. D. Leet, Comparison of two methods for interpretation of seismic time-distance graphs which are smooth curves, Trans. A. I. M. E., Geophysical Prospecting, 263-270, 1932). At that time no means were at hand to calculate the depth of penetration or the depth to a discontinuity, on the basis of a time-distance curve of the above form. Of late, however, several general analyses of the problem have been published but they are somewhat involved in their mathematical exposition (see preceding reference). This will be discussed later.

The exploration for structures in regions such as Kansas and Oklahoma was not quite so easy as finding domes in the Gulf Coast. The refraction method is not very reliable in detecting differences in depth of 50 or 100 feet at 5,000 feet below the surface. It has been found that much better results, at a lower cost, can be obtained by the reflection-method. This method consists, essentially, in interpreting the seismograms for waves which have been reflected from some discontinuity. In many instances it has shown itself to be a very powerful tool in solving geological problems, particularly in the exploration for oil-bearing structures.

The problem of reflection-shooting is to map some selected marker, or markers, such as for example the Viola limestone in central Oklahoma (E. McDermott, Application of seismography to geological problems, Bull. Amer. Ass. Petrol. Geol., 15, 1311-1334, 1931). Now the overburden of the Viola limestone, say, may be some 4,000 or 5,000 feet thick, and composed of shales, sandstones, and limestones. This overburden does not have a constant velocity, but by calibrating for an "average" velocity, we may assume it so over a restricted range. In order to make this "average" velocity as constant as possible, it is necessary to correct for the thin layer at the surface of the ground. This is commonly known as the weathering, and the velocity changes in it are very marked; it goes from a few hundred feet per second at the surface to 4,000

feet per second at a depth of only 40 or 50 feet. Below the weathered layer the velocity changes are not so rapid, varying from about 8,000 ft/sec close to the surface to some 12,000 ft/sec at a depth of, say, 5,000 feet. The usual method for obtaining the average velocity will be explained in detail.

General considerations

It is not the purpose here to give a complete analysis for wave-paths in elastic media. More extended treatments of the problem, for the cases of interest in seismic prospecting, are to be found in the publications of Ewing, Lest, Muskat, and Slichter Muskat (Morris Muskat, The theory of refraction-shooting, Physics, v. 4, 14-28, 1933) and Slichter (L. B. Slichter, The theory of the interpretation of seismic travel-time curves in horizontal structures, Physics, v. 3, 273-295, 1932) treat the problem in a somewhat general manner by the use of rather involved mathematics. The author hopes to present a definite picture showing the essentials necessary without recourse to complicated mathematical analysis. Simple examples are deduced from the more general expressions presented.

As has been mentioned before, the velocity in the overburden of a high-speed layer is not, in general, a constant. Even though it is possible to determine an average velocity for this overburden and use it in practice, still the fact remains that it is necessary to consider the curvature of the ray-paths in interpreting seismograms--to say the least, it is desirable. In order to do this, it is necessary to have a method whereby the ray-path may be determined and this entails a knowledge of how the velocity of propagation varies with depth of penetration. This problem, for the case which is of most interest in seismic prospecting, was first considered by Ewing (op. cit., p. 269; Ewing had derived an equation for penetration versus depth by another method a year or so before this publication). He assumed that the velocity-depth function, which we shall call V(y), was a steadily increasing function and depended only on the depth below the surface; no horizontal variation of velocity was allowed. The formula, although it gives the penetration of a wave for any shot-length, does not indicate how to obtain the depth to a discontinuity whose velocity is greater than the maximum velocity attained in the overburden.

Assume the surface of the Earth to be plane in the area under consideration, that is, the curvature of the geoid is neglected, and the axis OX (Fig. 1), lies in this plane. Ot, Oy, and OX are the time-, depth-, and distance-axes, respectively. The curve in the OtX plane then represents the time-distance curve, or X = F(t). Since the velocity does not change horizontally, the wave which originates at O and is recorded at any distance X travels a symmetrical path.

Consider the ray-paths of disturbances which originate at O and are recorded at various points on the axis OX. Now in the Figure, ΔX = increase in shot-length; Δt = increase in time due to increase of shot-length ΔX; V_o = velocity at the surface; i_o = angle of incidence in V_o, or angle of emergence; δs = change in length of path due to ΔX; and V_h = maximum velocity attained. Now record at the points X and (X + ΔX). XW represents a wave front and assuming ΔX to be small enough this may be taken to be a straight line perpendicular to the two ray-paths as shown in Figure 1. A wave travels such that

$$V_o : \sin i_o = V_1 : \sin i_1 = \ldots\ldots\ldots = V_h : \sin i_h \ldots\ldots\ldots \qquad (1)$$

Since the wave returns to the surface, $i_h = 90°$ and $\sin i_h = 1$, thus $\sin i_o = V_o/V_h$. We have in the Figure, assuming the proper order of infinitesimals, $i_o = \beta$, but $\sin \beta = \delta s/\Delta X = V_o \Delta t/\Delta X$. Equating we have

$$V_o/V_h = V_o \Delta t/\Delta X \text{ or } V_h = \Delta X/\Delta t$$

This equation tells us that the velocity represented by the time-distance curve is the velocity of propagation at the midpoint of the path.

Let us now consider the minimum time-paths. The time required for a wave to travel from a point, A, to another point, B, is

$$t = \int_A^B ds/V(y)$$

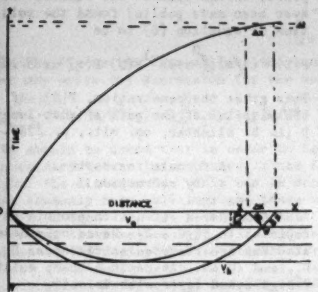


Fig. 1--Showing rays through the Earth and corresponding time-distance curve

or replacing the element of path by its equivalent form

$$t = \int_A^B [\sqrt{1 + y'^2} / V(y)]\, dx \quad \ldots\ldots\ldots \quad (2)$$

where V(y) is the velocity. In order to determine the minimum time-path we must minimize the integral given in equation (2). This can be done by the calculus of variations. [If the integral which we wish to minimize is given by

$$I = \int_A^B F(y,y')\, dx$$

the F(y,y') which will make this a minimum is found by solving the differential equation

$$d/dx(F - y' \partial F/\partial y') = 0$$

or $F = y' \partial F/\partial y' + K(x)$. Substituting from equation (2) for F, we immediately obtain

$$\sqrt{1 + y'^2} / V(y) = y'^2 / V(y) \sqrt{1 + y'^2} + K(x)$$

which by simple algebraic manipulation becomes

$$dy/dx = \sqrt{1/K^2(x)\, V^2(y) - 1}$$

(see Bliss, Calculus of variations, p. 49, equation (11)).] We find that the equation of the path of minimum time is given by

$$dy/dx = \sqrt{1/K^2(x)\, V^2(y) - 1} \quad \ldots\ldots\ldots \quad (3)$$

To determine the K(x) proceed as follows. Let V(x) be the velocity of the midpoint of the path of shot-length X, that is, the wave is returned from the bed which has the velocity V(x). The element of arc along the path is

$$dS = \sqrt{1 + y'^2}\, dx$$

At any point on the path the velocity is given by V(y) and hence we may write

$$\sin i_y = V(y)/V(x)$$

also $\sin i_y = dx/ds$, and $ds/dx = V(x)/V(y)$. This becomes upon substitution

$$V(x)/V(y) = \sqrt{1 + y'^2}$$

or

$$dy/dx = \sqrt{V^2(x)/V^2(y) - 1} \quad \ldots\ldots\ldots \quad (5)$$

We found, however, that the path of minimum time is given by the differential equation

$$dy/dx = \sqrt{1/K^2(x)V^2(y) - 1}$$

Since the expressions (3) and (5) must be equivalent we have

$$K = 1/V(x)$$

If P(x) be the penetration for a shot-length X we can write

$$\int_0^{x/2} dx = \int_{y=0}^{y=P(x)} dy/(\sqrt{1/K^2(x)\, V^2(y) - 1}) = \int_{y=0}^{y=P(x)} V(y)dy/\sqrt{V^2(x) - V^2(y)} \quad \ldots\ldots \quad (6)$$

which contains the unknown function V(y). This integral equation may be put in a form similar to the equation of Abel. In this manner Ewing (this work was done for a company engaged in seismic prospecting which has made good use of the formula for several

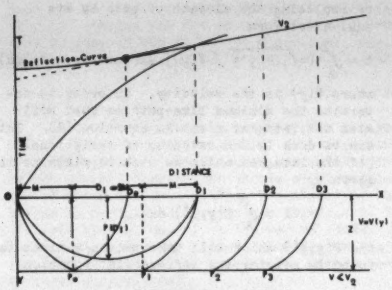


Fig. 2--Refraction-profile

years, though none of the results has ever been made public) found the solution of equation (6) to be

$$P(D) = (1/\pi)\int_0^D \cosh^{-1}V(D)\ K(x)\ dx \quad \ldots (7)$$

This gives the penetration, P(D), of the midpoint of the path of shot-length D (L. B. Slichter, op. cit., p. 276).

A formula for depth by refraction

Consider a refraction-profile as depicted in Figure 2. Waves originate at O and are recorded at distances D_0, D_1, and so on. At depth Z there exists a high-speed layer with velocity $V_2 > V(y)_{max}$. The wave travels through the overburden and is refracted over the interface between it and the high-speed layer. Now

$$\sin i_y = V(y)/V_2$$

but

$$\sin i_y = dx/ds$$

We obtain, in exactly the same manner as in the development of equation (5), the following

$$dy/dx = \sqrt{V_2^2 / V^2(y) - 1} \quad \ldots\ldots\ldots \quad (8)$$

where V_2 takes the place of the V(x) in equation (5). The time for any wave which is refracted over V_2 at depth Z below the surface and shot-length D is then given by

$$t = 2\int_{y=0}^{y=Z} (\sqrt{1/y'^2 + 1})\ dy/V(y) + (D - 2M)/V_2$$

2 M is usually, in seismic prospecting, called the mirage. M can be determined by making use of the differential equation of path through the overburden, or

$$dx = (1/\sqrt{V_2^2/V^2(y) - 1})\ dy$$

whence

$$\int_0^M dx = M = \int_0^Z dy/\sqrt{V_2^2/V^2(y) - 1}$$

The expression for the refracted time may now be written

$$t = 2\int_0^Z (\sqrt{1/y'^2 + 1})\ dy/V(y) - 2/V_2 \int_0^Z dy/\sqrt{V_2^2/V^2(y) - 1} + D/V_2 \quad \ldots\ldots\ldots \quad (9)$$

It will be noticed that the first refracted wave is also a reflected wave and this occurrs where (D - 2 M) = O or at a distance equal to the mirage. Thus we have a method for identifying a reflected wave in reference to the horizon from which it is reflected (H. M. Rutherford, Reflection methods in seismic prospecting, A. I. M. E. Tech. Pub. No. 486, p. 6). That is to say, the reflection-curve is tangent to the refracted line and this point of tangency marks the beginning of the refracted line. In actual practice a hard limestone, such as the Viola limestone in Oklahoma, has a velocity which is, within experimental error, constant--hence the word "line" in preference to curve. Now for distances shorter than O D_1 the shortest time-path is through the overburden and the penetration for any such ray is given by formula (7); the greatest velocity attained by such waves is V(x), where x is less than O D_1. At distances greater than O D_1 the shortest time-path is one in which the wave is refracted over the high-speed bed. The time for a wave which travels entirely in the overburden is

$$t = \int_{x=0}^{x=D} \sqrt{1 + y'^2}\ dx/V(y)$$

or since $y' = \sqrt{V^2(x)/V^2(y) - 1}$

$$t = \int_{x=0}^{x=D} V(x)\, dx/V^2(y)$$

In the Figure the time will be the same over the two paths at some distance D_1, whence we may write the expression for the depth

$$\int_{x=0}^{x=D_1} V(x)dx/V^2(y) = 2\int_0^Z V_2 dy/V(y)\sqrt{V_2^2 - V^2(y)} - 2/V_2\int_0^Z dy/\sqrt{V_2^2/V^2(y) - 1} + D_1/V_2 \quad \cdots \quad (10)$$

It should be noted that in order to determine an accurate expression for V(y) it is necessary to use later phases, since X = F(t) does not represent the first arrival beyond the distance D_1. This can be done. Furthermore, in actual geophysical practice we commonly have well logs and these can be used as an aid in determining the correct form to use. It will be noticed that the difficulty of solving for Z depends upon the form of the function V(y). If V(y) is such that the velocity varies as a linear function of the depth, then we obtain a formula which has been worked out by Ewing and Leet (Maurice Ewing and L. D. Leet, Seismic propagation-paths, Trans. A. I. M. E., Geophysical Prospecting, 245-260, 1932).

The following is a practical example which illustrates the formula. This same example can, of course, be worked by a very simple analysis but it serves our present purpose. Suppose that V(y) is a constant, say V_o. From this we have the fact that $V(y) = V_o$ and also $V(x) = V_o$. Let V_2 be the velocity in the high-speed layer. By making use of equation (10) we can derive a formula for the depth V_2 below the surface. The equation then becomes, upon substitution,

$$\int_{x=0}^{x=D_1} V_o dx/V_o^2 = 2\int_{y=0}^{y=Z} V_2 dy/V_o\sqrt{V_2^2 - V_o^2} - 2/V_2\int_{y=0}^{y=Z} V_o dy/\sqrt{V_2^2 - V_o^2} + D_1/V_2 \quad \cdots \quad (11)$$

or

$$D_1/V_o = 2\, V_2 Z/V_o\sqrt{V_2^2 - V_o^2} - 2/V_2(V_o Z/\sqrt{V_2^2 - V_o^2}) + D_1/V_2$$

We can now write the above formula in two well-known forms

$$D_1/V_o = 2Z/V_o \cos i - 2Z\tan i/V_2 + D_1/V_2 = 2Z/V_o \cos i + (D_1 - 2Z\tan i)/V_2$$

since $\sin i = V_o/V_2$. It can be shown to be, by some algebraical manipulation

$$Z = D/2\sqrt{(V_2 - V_o)/(V_2 + V_o)}$$

Reflection-depth formulas

We first develop the formula for a finite number of beds. In case the section can best be approximated by assuming a finite number of beds, each of which has a constant velocity, this formula can be used to good advantage. An example using this case is shown and explained later. Further, if the section is such that the velocity is a continuous function of the depth, we can, with the same analysis, derive a general formula for the depth of a single discontinuity. This is done by expressing infinite sums as integrals. This method of deriving the differential equation of the path has the advantage of simplicity and is direct.

Assume a series of parallel layers with the velocities $V_1, V_2, \ldots, V_n$. Consider each of these layers to be homogeneous and isotropic throughout its extent. The thicknesses corresponding to these velocities are $Z_1, Z_2, \ldots, Z_n$, respectively. For convenience we repeat Snell's law

$$V_1 : \sin i_1 = \ldots = V_n : \sin i_n$$

For any particular path the ratio of the velocity to the sine of the angle of incidence is a constant. Call this constant value, K, or

$$K = V/\sin i$$

Thus K may be considered as a parameter which determines the particular path the wave would follow.

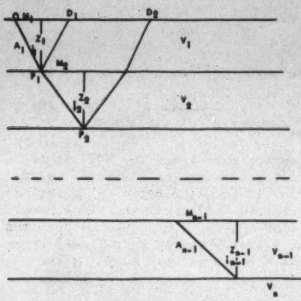


Fig. 3--Effect of several beds

The expression for the time may be written from Figure 3 as

$$t/2 = A_1/V_1 + \ldots\ldots\ldots + A_{n-1}/V_{n-1}$$

and the distance

$$x/2 = M_1 + \ldots\ldots\ldots + M_{n-1}$$

Figure 3 shows that

$$A = Z/\cos i$$

but since

$$\sin i = V/K$$

$$\cos i = \sqrt{K^2 - V^2}/K$$

and

$$A = ZK/\sqrt{K^2 - V^2}$$

If this value for A be substituted in the expression for time, we get

$$t/2 = Z_1K/V_1\sqrt{K^2 - V_1^2} + \ldots\ldots\ldots + Z_{n-1}K/V_{n-1}\sqrt{K^2 - V_{n-1}^2} \ldots\ldots \quad (12A)$$

Further, from Figure 3

$$\tan i = M/Z$$

Since the values for the sine and cosine are known

$$\tan i = V/\sqrt{K^2 - V^2} \text{ and } M = ZV/\sqrt{K^2 - V^2}$$

Thus we can write the expression for the distance

$$x/2 = Z_1V_1/\sqrt{K^2 - V^2} + \ldots\ldots\ldots + Z_{n-1}V_{n-1}/\sqrt{K^2 - V_{n-1}^2} \ldots\ldots \quad (12B)$$

We can write these as

$$t = 2\Sigma KZ_1/V_1\sqrt{K^2 - V_1^2}$$

$$x = 2\Sigma Z_1V_1/\sqrt{K^2 - V_1^2}$$

$$M = \Sigma Z_1V_1/\sqrt{K^2 - V_1^2}$$

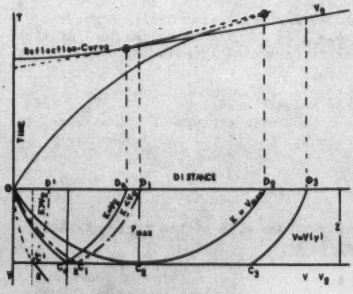


Fig. 4--Ray-paths for various values of K

Let the thickness of each of the layers become indefinitely small, or dy. Now with every Z there is associated a definite value of V, hence we may say that V is a function of the depth y, or V = V(y). Thus the foregoing expression becomes -

$$t = 2\int_0^Z K\,dy/V(y)\sqrt{K^2 - V^2(y)} \ldots\ldots \quad (13A)$$

$$x = 2\int_0^Z V(y)\,dy/\sqrt{K^2 - V^2(y)} \ldots\ldots \quad (13B)$$

$$M = \int_0^Z V(y)\,dy/\sqrt{K^2 - V^2(y)} \ldots\ldots \quad (13C)$$

These expressions could all be obtained from equation (3) by integration. When we select K, this determines an initial entrance or emergent angle for the ray and this gives rise to several ray-paths, such as, for

example, the ray-paths OP_1D_1, $OP_1P_2D_2$, etc., in Figure 3. The differential equation of path is then

$$y' = \sqrt{K^2/v^2(y) - 1}$$

where K is a parameter.

If a layer has the velocity K, then the wave returns back to the surface from this layer (by reflection or refraction) and this ray-path is a minimum path. However, as has been mentioned, corresponding to each value of K there are ray-paths other than the minimum (Morris Muskat, op. cit., p. 16), such as, for example, those of reflected rays at other angles than the critical. Figure 4 illustrates this point. This case is the one of most interest in practical problems since we wish to use distances on the surface which are quite small.

Now consider Figure 4. The ray-path $O C_0 D_0$ represents a ray which is reflected at the critical angle, that is, $K = V_2$. At this point it will be noticed that the line marked V_2, the velocity in the high-speed marker, and the reflection-curve are tangent. Values of the parameter K, such that $K > V_2$, correspond to ray-paths which are reflected at angles smaller than the critical angle. This is shown in the Figure by OC' D'. Those values of K such that $V(y)_{max} \leqq K < V_2$ give rise to ray-paths corresponding to $O C_1 D_1$. Now as K approaches $V(y)_{max}$ the ray-path approaches $O C_2 D_2$ and the reflection-curve approaches $X = F(t)$. In the limit the penetration, $P_{max} = Z$ and the ray-path $O C_2 D_2$ is tangent to the bed V_2 and this represents both a wave which is reflected from V_2 and yet refracted through the overburden.

The foregoing discussion suggests a way to identify reflected phases on seismograms. First we shoot a refraction-profile, which gives the various velocities encountered. Upon this basis we can evaluate the seismogram and plot the various phases. Hence we not only can identify a reflected phase as such but can also correlate it with some definite discontinuity. This method is not restricted to regions which have wells, which is its major advantage. Also it might be possible to extend the depth of exploration far beyond the depths now attained.

The usual procedure in the identification of reflections is somewhat different from the method outlined above. This method might be called the "calibration" method, since it depends upon a calibrated average velocity. One method of calibration is to shoot at various depths in a well and thus obtain an average velocity. Shots are then taken for reflections and by picking waves which have times that correspond to times from horizons which are arbitrarily chosen as likely to reflect, the reflection is "identified." This method is open to serious objections and is limited to regions in which wells have been drilled. It could not be used for depths beyond some 6,000 or 7,000 feet, with a few possible exceptions. In refractions the velocity of the refracting bed is determinable and is usually a sufficient criterion for the identification of the bed (D. C. Barton, The seismic method of mapping geologic structure, A. I. M. E., Geophysical Prospecting, 572-624, 1929). In this method, however, the velocity of the reflecting-bed is not determinable and hence horizons may be jumped without suspicion of the fact.

Actual practice

Consider the waves which originate at O, in Figure 5, and suffer reflection at a point, P, at the interface between V_1 and V_2. The time of travel of the ray-path OPR is designated by T and the distance on the surface by X. If the depth is Z, the following equation may be written, providing the surface and the interface are parallel

$$Z = (1/2)\ (V_1^2 T^2 - X^2)^{1/2} \quad \ldots\ldots\ldots \quad (14)$$

This is the formula most generally used in computing the depth of horizons by the reflection-method.

Now, the arrangement is made so that MP lies in a well. The geologic column is obtained. It is noted on the geologic column that V_2 is a bed which should produce reflections; say that V_1 is composed mostly of shales and sandstones and V_2 is a hard limestone. A shot is fired at point P and recorded at R. A variation of this, which amounts to the same thing, is to place a geophone or microphone at P and shoot at

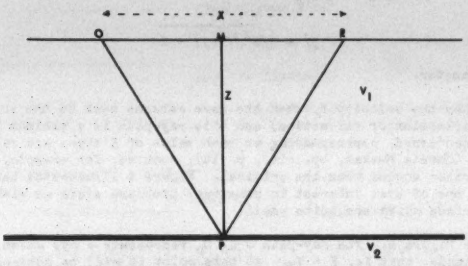


Fig. 5--Path of a reflection in the simple case

either O or R. The time of transit between P and R is then measured. The distance PR is divided by this time and thus the average velocity is computed. This may be done for one or several horizons. After this, shots are placed on the surface and records obtained for various values of X. The depth as taken from the geologic column, and the average velocity as determined by shooting in a well, are substituted in formula (14). This gives the time the reflected wave should take in going over the path OPR. Thus, by correlating this time with the phases on the seismogram, the reflected wave is identified. The reliability of this method depends upon: (1) Assuming that the phase picked is the phase which correlates with this horizon, and (2) knowing that the horizon picked will give a reflection.

A variation of this method is to take shots at O and record at R. From the geologic column, beds are picked which might give reflections. From the records, times for various phases are picked. By substituting these times and the depths as found from the geologic column, the average velocity to any bed may be determined and the reflected phases are identified on the seismogram. If several values for T, from the same horizon, are obtained then an average is taken for the final determination.

Additional information in regard to the identification of a reflected phase on the seismogram may be obtained by placing the shots as in Figure 6. There is very little difference between the length of paths OP_1R_1, OP_2R_2, and so on, provided $R_{i+1} - R_i$ is not too large and also V_2 (that is, the bed with velocity V_2) must not slope at too great an angle. Upon these assumptions the reflected times will not change by any appreciable amount. Other types of waves, however, especially the surface-waves, will show large changes in comparison with the reflection-times.

Upon the basis that the overburden has a constant velocity it might appear that the best method for obtaining an average velocity, as well as the depth, would lie in

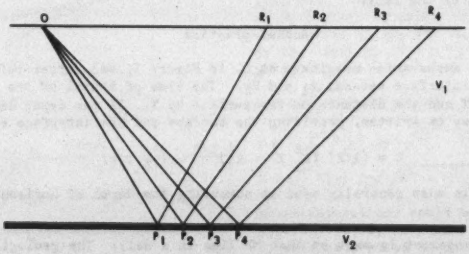


Fig. 6--Arrangement of recording-stations for identification of reflected phase

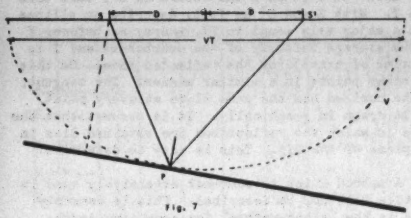


Fig. 7

Fig. 7--A graphical method for mapping structure by reflections

solving several observational equations by means of least squares. That is, take equation (14) and put it into linear form. Rewriting equation (14)

$$V^2T^2 = X^2 + 4Z^2$$

where V is the velocity and T the total time of transit of the reflected wave, X is the horizontal distance on the surface, and Z is the depth below the surface to the reflecting-horizon. This equation can be written as

$$Aw - B = K \quad \ldots\ldots\ldots \quad (15)$$

where $A = T^2$, $K = X^2$, $B = 4Z^2$, and $w = V^2$. Such a system of observational equations could be solved quite easily by means of least squares. However, there are several factors which would prevent such a solution from giving reliable results: (A) Times of reflection-arrivals on records could not be obtained with great enough accuracy; (B) if distances were taken far enough apart to reduce the effect of time-errors, then the same equation could not hold because the same average velocity cannot be used over a wide range of distances, due, among other things, to curvature of ray-path; (C) large errors creep in by way of the weathering correction.

Some reflection-formulas

We assume that the use of an average velocity will not introduce too great errors in our depth-computations. This means that the distances on the surface are not to vary over too large a range. In this restricted region the overburden of the reflecting horizon is taken to be homogeneous and isotropic and we denote its velocity by V.

In Figure 7 let S be the origin of a wave which suffers reflection at a point, P, and hence returns back to the surface. The total path which this wave travels may be denoted by SPS'. The time for the reflected ray may then be written

$$T = (SP + S'P)/V \quad \ldots\ldots\ldots \quad (16)$$

If (SP + S'P) is a minimum, T will be a minimum. This time will be a minimum if P is a point on an ellipse to which the bed is tangent at the point P (principle of least time). S and S' will be the foci of the ellipse. The origin of the ellipse may be considered to be at SS'/2. From equation (16)

SP + S'P = VT = length of major axis

The length of the semimajor axis is VT/2, and of the semiminor axis,

$$[(V^2T^2/4) - D^2]^{1/2}$$

where D = SS'/2. If X be the horizontal distance on the surface and Z the depth of P normal to the surface, we may write the equation of the ellipse

$$X^2/(V^2T^2/4) + Z^2/[(V^2T^2 - 4D^2)/4] = 1 \quad (17)$$

The analytic treatment of this equation becomes too unwieldy to use in actual practice. The equation can be used, however, as a basis for a graphical method for mapping horizons.

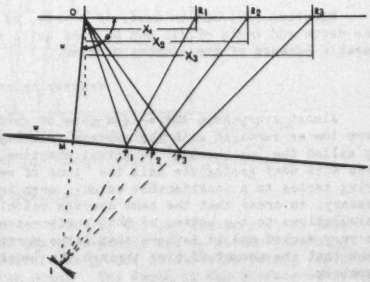
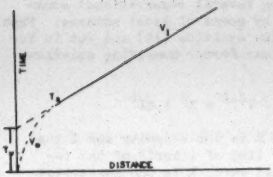


Fig. 8--Use of image-point in computing depths



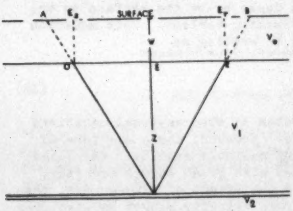


Fig. 9--Surface-correction

Shoot at a point S and record at S'; call this time T. With S and S' as foci, describe an ellipse with a major axis equal to VT, where, as before, V is the average velocity of the overburden and T is the time of travel for the reflected wave. Do this for other points in a similar manner. The tangent, if the horizon has the same slope at every point, may be drawn in graphically. It is assumed that the plane in which the reflections are obtained lies in the plane of the dip. This is easy to determine.

A method which is somewhat extensively used in practice will now be described. This is commonly known as the "slope-method" for computing depths. Consider Figure 8. O is the origin of the rays which are reflected at the points P_1, P_2, P_3 and recorded at R_1, R_2, R_3. The distance $OR_1 = X_1$. As before, V is the velocity of the overburden. 1 is the image-point of these reflected waves. Call the perpendicular distance from O to the reflecting horizon H, that is, O M in the Figure. Now O M = M I and O P_1 = I P_1. The slope of the reflecting horizon is w. θ is the angle between OX and O M. From the Figure it is seen that w = (0 - 90°). For any ray reflected from a point P

$$T = OP/V + PR/V = (IP + PR)/V = IR/V$$

or

$$IR = VT$$

By the law of cosines

$$\cos \theta = (X^2 + 4H^2 - V^2T^2)/4HX \quad \ldots\ldots\ldots \quad (18)$$

The depth is usually measured perpendicular to the surface of the ground, hence

$$Z = H/\cos w$$

In the case w = 0 then equation (18) reduces to equation (14). The method is put to use somewhat as follows. The times for the reflections are taken from the records. These times are multiplied by the average velocity. A suitable scale is chosen and then with R_1 as a center an arc is described with a radius equal to VT_1. The intersection of the arcs (corresponding to several values of i) then locates the image-point 1. This point is connected to the shot-point. The bisector normal to O1 is then the required reflection-surface.

Equation (18) can be used, of course, to construct nomographic charts from which the depth and angle of dip can be read quite easily. This method, in general, is preferable because of the economy of time.

Weathering correction

Almost everywhere there is a zone of surface-material in which the velocity is very low as compared with the average velocity of beds below it. This zone is commonly called the "weathering" in actual practice, although it does not, in general, coincide with what geologists call the "zone of weathering." The thickness of the weathering varies to a considerable extent, even in a single small area. Hence it is necessary, in order that the same average velocity may be used in an area, to refer all calculations to the bottom of this surface-zone. The curvature of path in this zone is very marked and it is here that large errors creep into the calculations due to the fact that the amount of time through the "weathering" cannot be determined very accurately.

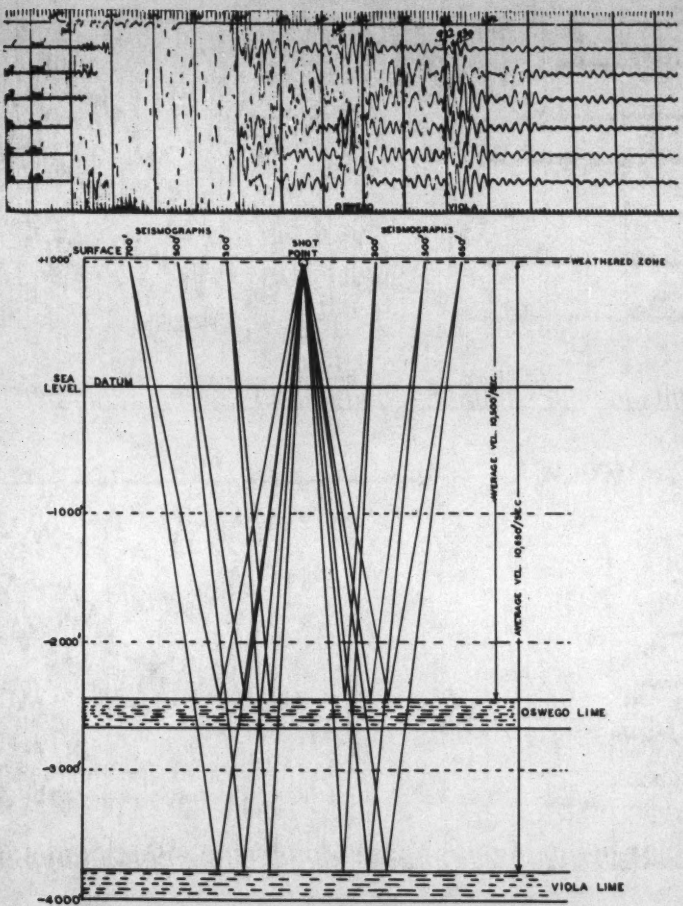


Fig. 10--Illustration of a method for identification of reflections

Usual practice

Figure 9 shows a diagram of a method of treating the surface-correction zone. W_s is the thickness of the weathered zone at the shot-point, and W_r at the recording point. E_s is the elevation of the surface of the ground at the shot-point, referred to mean sea-level, and E_r at the recording point. The depth of the surface-correction zone W is small in comparison with the depth Z, hence the path E_sO can be taken as

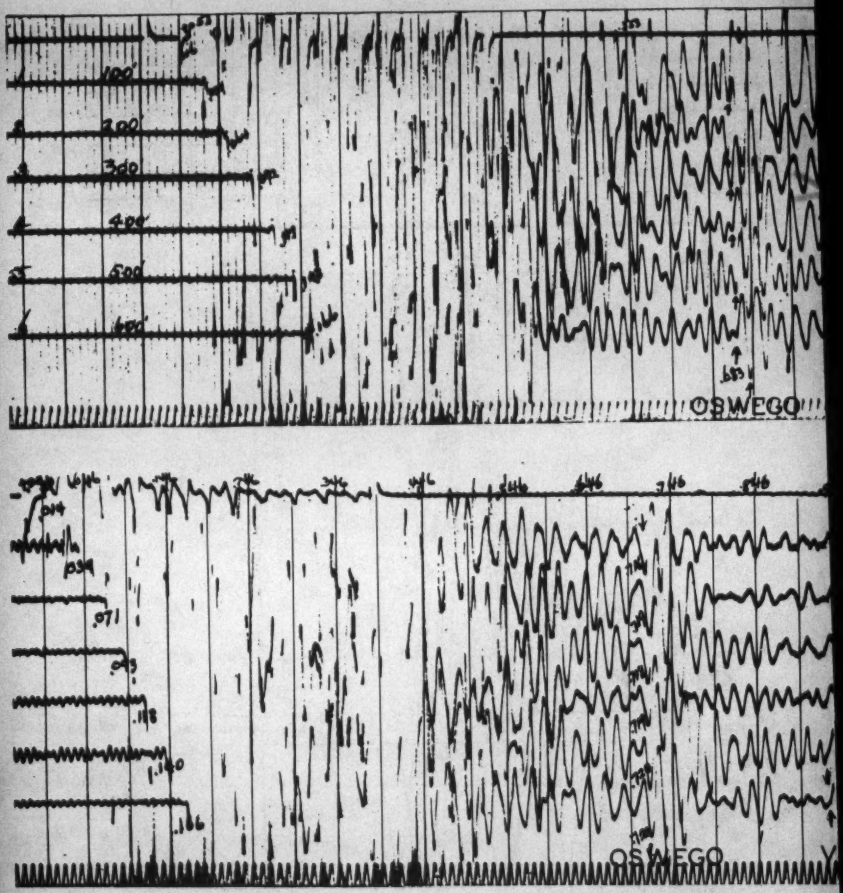
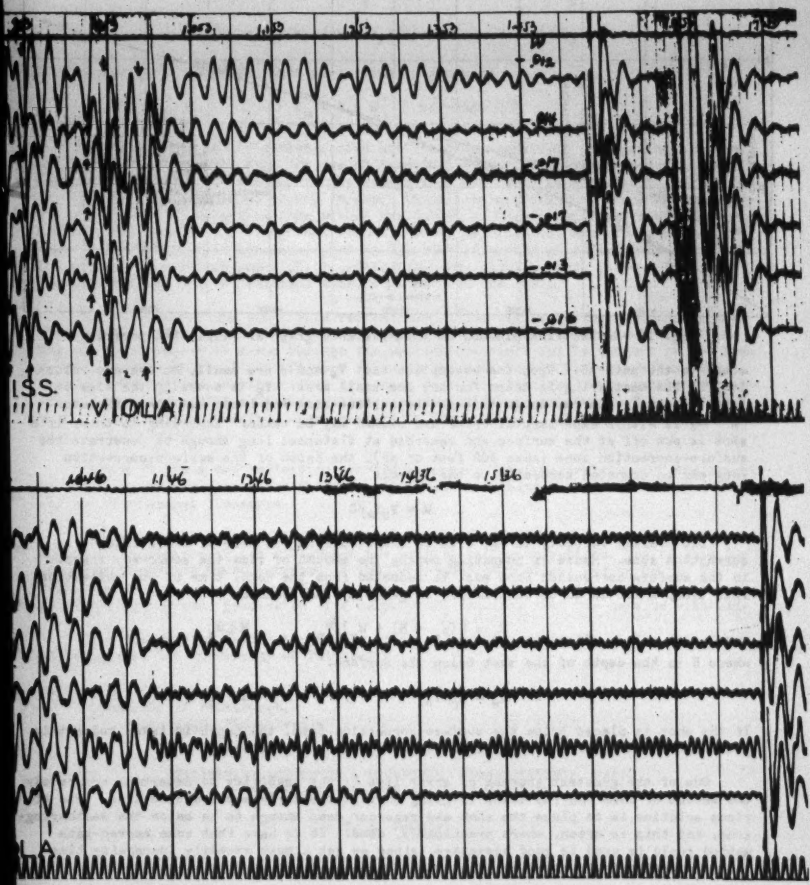


Fig. 12--Examples of



reflection-records

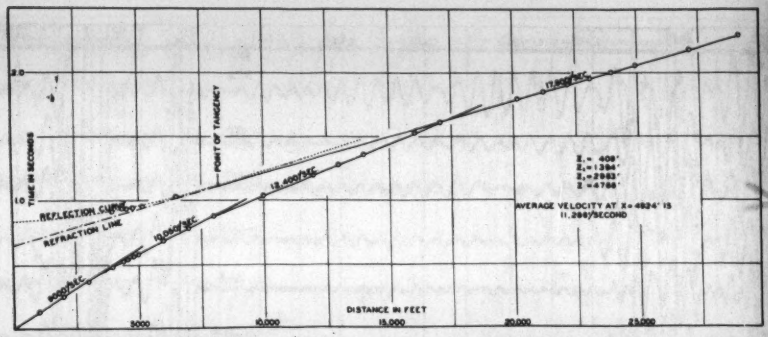


Fig. 11--Reflections plotted on time-distance graph of refraction-profile

equal to the path AO. Upon the assumption that T_w and W are small, an average velocity for the weathering is taken for any one small area. T_a is actually the time it takes for the sound-ray to go through the surface-zone and back, but the difference $T_w - T_a$ is within experimental error and either may be taken. According to this, if a shot is put off at the surface and recorded at distances long enough to penetrate the surface-correction zone (some 200 feet or so), the depth of the surface-correction zone can be computed according to the formula

$$W = V_o T_w/2$$

The average velocity in any area is computed from the base of the surface-correction zone. Hence in computing depths the amount of time the sound-ray travels in the surface-correction zone must be deducted from the total time of the reflection. This time, which is to be subtracted, is given by the formula

$$T_w = [(W_s - H) + W_r]/V_o \qquad H < W_s$$

where H is the depth of the shot below the surface.

$$T_w = W_r/V_o \qquad H > W_s$$

If the shot is placed below the surface-correction zone, the depth is taken below this point and the base of the surface-correction zone at the recorder.

One of the greatest sources of error lies in the inability to determine accurately the amount of time the ray takes in going through the surface-correction zone. One obvious solution is to place the shot and recorder deep enough to be below the weathering-zone, and this is often, where practicable, done. It is here that some curved-path method could be used to good advantage, since we get almost steadily increasing time-distance weathering-curves.

Reduction to mean datum

To reduce to mean datum, the average elevation at the midpoint between shot and recorder is taken, diminished by the average value of the surface-correction zone between these two points. If the shot is below the weathering, the mean is taken between this depth and the surface-correction at the recorder. Written as a formula, this gives

$$E = [(E_s + E_r)/2] - [(W_s + W_r)/2] \qquad H < W_s$$

$$E = [(E_s + E_r)/2] - [(H + W_r)/2] \qquad H > W_s$$

If Z be the depth computed, then mean datum is given by

$$D_m = E - Z \qquad \text{at point } X/2$$

Figure 10 shows a reflection-record and its interpretation. The geologic column was obtained from a well-log. By use of formula (14), after proper corrections had been made, the average velocity to the Oswego lime was found to be about 10,500 ft/sec and to the Viola lime about 10,650 ft/sec. It will be noticed that there is very little evidence of a reflection from either the Hunton or Mississippi lime-series, which should occur between the Oswego and Viola lime-series, that is, when it is present. This is the method most generally used in the identification of reflections on records. The author, in a former paper (H. M. Rutherford, op. cit., p. 20), gives a form for the computations with a practical example taken from the field.

Figure 11 shows the graph of a refraction-profile and on it the reflections are also plotted. This profile was interpreted on the basis of rectilinear propagation. The reflection-curve is drawn through the reflection-points and is tangent to the line which has the velocity 17,800 ft/sec. This corresponds to the Viola limestone and thus the reflections are identified as coming from this horizon. This method does not depend on a knowledge of the geologic column, though it is always of some advantage to have this information where possible. This method is applicable where no wells have been drilled.

Figure 12 shows two reflection-profile records. The interpretation of the phases is based on the analysis given in Figure 10. Note the phase marked Mississippi, that is, the Mississippi limestone.

The author wishes to thank Professor James S. Taylor of the Department of Mathematics of the University of Pittsburgh for many valuable suggestions. He is also indebted to Professor Henry Leighton of the Department of Geology, and to Dr. A. E. Staniland of the Department of Mathematics for criticism of the paper. The data are published by the kind permission of a company who requests that its name be withheld.

This was written during the tenure of a graduate assistantship in the Department of Geology at the University of Pittsburgh.

Seismograph Station,
University of Pittsburgh,
Pittsburgh, Pennsylvania

PRELIMINARY REPORT ON A LOW-POWER, HIGH-FREQUENCY, RADIO TELEPHONE- AND TELEGRAPH-TRANSMITTER

T. S. McCaleb

(Abstract)

The report describes a practical low-power radio telegraph-and telephone-transmitter suitable for reliable communication at geophysical frequencies over distances up to 50 miles when used with a simple radiator in the field and working with a sensitive receiver such as the ones now commercially available. The transmitter is one of a series being designed for portable use in the field by the Harvard University Institute of Geographical Exploration. It was developed in cooperation with the Harvard Seismograph Station, under the auspices of the Harvard Committee for Geophysical Research, for use in the Station's program of seismic surveying.

A high order of frequency stability is attained with either crystal- or self-control. The change from one type of control to the other is effected by altering a single connection. A 12-volt battery supplies power and is called upon to deliver

about 14 amperes for normal operation. A neon tube replaces several meters in controlling adjustments. Compactness of design and ready accessibility for repairs are features.

It is pointed out that wave-lengths of the order of five to nine meters offer tremendous advantages in the problem of simple and efficient field communication and that it is important that those engaged in geophysical prospecting of various types should request of the Federal Radio Commission a portion of the many available channels in this region before commercial organizations in other lines absorb them.

Harvard University Institute of Geographical Exploration,
Cambridge, Massachusetts

ADDRESS OF WELCOME AT THE GEORGETOWN UNIVERSITY

Coleman Nevils, S.J.

It indeed gives me great pleasure to welcome you to Georgetown in the name of the Directors of the University. I feel that you are conferring an honor upon our science departments in accepting whatever hospitality we can give you for your sessions this morning.

I am sure you realize that the University for many years has been extremely interested in your particular science, and there is no Department of the University which has greater cooperation on the part of the Directors. I presume that I am not departing from the usual procedure when I pay tribute to the late Father Francis A. Tondorf, S.J., who did so much for the Georgetown Seismological Observatory and for your Society, of which he was a devoted member. I feel that there will never be a gathering of seismologists in our University which will not pay tribute to this distinguished scientist.

I regret that it is not possible for me, owing to my official engagements, to remain here for your sessions. I trust, however, that I shall have the pleasure of meeting you at lunch. May I in these few words express our sincerest welcome to you at Georgetown.

Georgetown University,
Washington, D. C.

AN ACCELEROMETER FOR RECORDING STRONG EARTH-MOTIONS

M. W. Braunlich

Before describing the instrument which I propose for the recording of strong earth-motions, I shall, for the benefit of those who have not followed the argument for a short-period instrument, point out its advantage over the other types. These advantages are stability of the instrumental characteristics, ability to measure large ground-displacements, and the greater ease with which a complete interpretation of the record may be obtained.

The instrumental characteristics of the short-period instrument are less affected by the acceleration to which they are most certainly subjected during an earthquake. This may readily be seen by substituting the new component of acceleration in the following formula for the period of a horizontal pendulum

$$T = 2\pi\sqrt{L/(ig + a)}$$

where L = equivalent length of pendulum, i = the sine of the angle of inclination of the axis of rotation, T = the period of pendulum, g = the acceleration due to gravity, and a = the component of the Earth's acceleration in a direction perpendicular to the motion of the inertia-mass and in a plane perpendicular to the axis of rotation.

For a pendulum with a natural period of three seconds, a length of one foot and a component of ground acceleration (a) which varies from +0.1 to -0.1, the fundamental

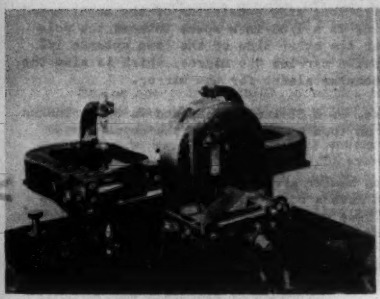


Fig. 1--Instruments for measuring the three components

Fig. 2--All parts entering into the vertical instrument

period varies from 2.28 seconds to 5.83 seconds, and with an acceleration which varies from +0.15 to -0.15 the natural period varies from 2.05 seconds to infinity, and then the boom will tend to rotate through an angle of 180°. As the fundamental period of the instrument becomes shorter, the quantity ig becomes larger and the quantity a becomes of less importance.

The extremely short-period instrument is capable of measuring the acceleration of large ground-motions as well as those of a small ground-motion, but the long-period instrument as developed thus far cannot measure large displacements due to the fact that any instrument based on a rotating element is necessarily confined to a small angle of rotation if any degree of accuracy is to be obtained. The short-period instrument has of course only a small angular displacement for even large accelerations.

Instruments which have a natural period in the range of the period of the vibrations which are to be measured or long-period instruments give records which are extremely difficult of interpretation as compared with those of the short-period instrument. The long-period instruments require a double differentiation of the record in order to determine the accelerations. This is an arduous task and has the disadvantage that no means have yet been devised for its accurate accomplishment. The instrument which has its period well in the range of those periods of the vibrations which are to be measured requires even more work, as the double differentiation is necessary and must be preceded by two integrations. The ordinates of the record, the first integration, and the second integration must then be added and replotted before the differentiates can be undertaken. All of these processes become practically impossible with an instrument in which the characteristics change continually (H. A. Wilson, The calculation of the motion of the ground from seismograms, Physics, v. 2, No. 3, 1932).

Of course the Piezo electric and carbon-pile machines are simply accelerometers with extremely short period with electrical mechanisms for producing high magnification.

Due to the instability of radio tubes and the uncertainty of carbon piles, etc., they are suitable only for use in the laboratory or where wave-form is not of fundamental importance.

At the Massachusetts Institute of Technology we have developed an accelerometer of the Wood-Anderson type, following very closely the instrument suggested by Wenner of the Bureau of Standards, with the exception that the natural period has been reduced to 1/30 second (Frank Wenner, A proposed accelerometer for use in a seismic region, Eastern Sec. Seis. Soc. Amer., Proc. 1930 meeting).

The inertia-mass of the system consists of a rectangular copper loop 3/8 inch by 1-1/8 inch. One of the longer sides of this loop is a copper tube through which

passes the suspension-wire. The ends and remaining side of the loop are made of sheet copper 0.01 inch thick and 1/4 inch wide. The long side consisting of the sheet-metal has a radius of curvature of 3/8 inch and runs in a 1/32-inch space between the pole pieces of a cobalt-steel magnet. The tube at the other side of the loop extends 1/2 inch beyond the end of the loop. This extension carries the mirror, which is also the focusing lens for the optical lever, and a counterbalance for the mirror.

The torsion-member is of phosphor bronze, is 0.01 inch thick, and is 3-1/4 inches long between supports, there being 13/16 of an inch at each end of the copper tube where it is made fast.

The transverse-vibrations of the torsion-member are damped out by passing the suspension-wires through small washers which have a hole 0.0035 inch larger than the wire and are lubricated with a heavy oil. These washers are cemented in place after the suspension and magnet have been adjusted.

The suspension-wires are held by two small chucks which may be rotated so that the position of the inertia-mass may be easily controlled.

The construction of magnets presented a great difficulty as we had considerable trouble in having them manufactured in such a way that they would furnish sufficient flux-density for damping-purposes, although, according to theoretical considerations, there should have been little trouble. This difficulty came from our trouble in obtaining sound castings, and the inability of magnet manufacturers to magnetize such large specimens. We experienced some difficulty in obtaining a cobalt steel with sufficiently high residual to warrant its use in these magnets, as there is to the best of my knowledge only one manufacturer in the country who makes it and that company will not make the magnets. This difficulty in locating the manufacturer was apparently due in a large part to unwillingness of the makers of other steel to aid us in gaining contact with the people who did manufacture it.

We attempted to make the magnets ourselves but failed to do so successfully and finally had them cast by a professional magnet manufacturer. However, it was necessary to magnetize them ourselves after they were received. The material is quite hard to handle in large sections either in the rolled or cast state, and even the magnets which are finally in use show flaws in the casting when examined under the X-ray.

It is also very important that the design of such magnets be carefully carried out if they are to be successful.

The magnets now on the instruments, however, are able to furnish a flux-density more than sufficient to damp them critically, and they are furnished with a short-circuiting device in order to adjust the damping to the desired amount.

The general characteristics of the instrument as set up here are: Natural period, 1/30 second; gravity-acceleration, 1-3/4 inch on the record; length of light-lever, 40 inches; and damping-ratio, 1-20, 70 per cent critical.

If it is thought that the static magnification is rather small, this may be doubled by substituting a plane mirror for the lens and moving the lens to a stationary position so that a double reflection may be obtained. This would make a gravity-acceleration give a displacement of approximately 3-1/2 inches on the record.

I believe that study of the records taken at Long Beach, California, on March 10, 1933, will show the advantages of using this shorter-period instrument together with the changes for greater magnification suggested in the previous paragraph.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

A NEW TABLE OF OBSERVED TRAVEL-TIMES OF EARTHQUAKE WAVES, FOR DISTANCES BETWEEN 10° AND 180° AT ONE-DEGREE INTERVALS, APPLICABLE ONLY TO EARTHQUAKES OF SHALLOW FOCUS

James B. Macelwane, S.J.

During the years 1926-27, a series of tables of supposed travel-times of earthquake-waves was mimeographed and distributed by the Department of Geophysics of Saint Louis University for purposes of comparison and further study. In those tables the data were drawn from many sources. The travel-times given for P and S were practically those published by A. Mohorovičić but were graphically transformed from a basis of kilometers per second to that of degrees per second and graphically interpolated to tenth-degrees. The travel-times which were adopted for the reflected waves were based partially on studies made in the Geophysical Laboratory of Saint Louis University and partly on calculation where the observations were inadequate. The travel-times of core-waves were graphically interpolated from those published by Gutenberg. The speeds of L, M, W_1, and W_2 had been worked out by Macelwane and Byerly at the University of California, as had also the mile- and kilometer-equivalents of the distances in degrees.

The whole set of five tables was sent for trial to a large number of workers in the seismological field and criticisms of their accuracy were requested. They were compared by a number of seismologists, including Lehmann, Repetti, Hodgson, and Stechschulte, with observations on particular earthquakes. While better than previous tables in some respects, they were found to give large residuals and to contain systematic errors; for they had an arbitrary zero of reference and they were based on averages.

The recent studies on deep earthquakes by Turner, Wadati, Serase, Stechschulte, and Brunner have shown conclusively that one set of tables of average travel-times applicable to all earthquakes is an impossibility. The variations introduced by depth of focus are too great. It is clear that every earthquake has its own travel-times. Nevertheless, earthquakes of very moderate depth form the majority of those recorded. Hence, a table of travel-times which are characteristic of this latter class will be of very great use to seismologists.

Two recent earthquakes seem to furnish an adequate basis for such a table. The earthquake which occurred in the Tango District, Japan, March 7, 1927, was carefully investigated by Hodgson and a part of his results was published in the Bulletin of the Seismological Society of America in 1932. This earthquake was not of such extreme intensity as to prevent many of the nearby stations from securing legible records; but this very fact, together with the position of the epicenter in relation to the stations of the world, restricted the range of satisfactory registration to about one hundred degrees epicentral distance.

On the other hand, the earthquake which occurred in Hawke Bay, New Zealand, February 2, 1931, was so extremely violent that the usefulness of the records made of its phases after the arrival of the direct P-waves is largely restricted to the greater distances. Fortunately New Zealand is so far from the stations in the Northern Hemisphere that large numbers of excellent records were obtained in the second quadrant and some quite close to the anticenter. This earthquake is being investigated in great detail by C. G. Dahm working on a Storrow Fellowship of the National Research Council. He finds that the travel-times of the Hawke Bay earthquake agree so well with those of the Tango earthquake that the focus of the former must have been at approximately the same depth as that of the latter. This was found by Hodgson to be about twelve kilometers. Consequently, the two earthquakes so complement each other as to furnish one complete set of curves covering the entire range of distances from 10° to 180°. From these the new Table of travel-times has been compiled.

The meaning of the word origin and of the symbol O for time at the origin involves such ambiguity that it has been thought best to avoid the use of either. In the past, there was so little precision possible in the determination of the precise meaning of the null-point in time-distance graphs that the ambiguity is easily understood. In fact such all-inclusive symbol was practically necessary.

Recently, however, it has become possible to distinguish clearly between the time at which a wave leaves the focus and the time at which it arrives at the epicenter. In the case of the Tango earthquake, Hodgson found that the time-interval between the start of the wave and its arrival at the epicenter was approximately two seconds. He also found that the null-point of the time-distance graphs in ordinary use, including those of Gutenberg, of A. Mohorovičić, and of the writer is eleven seconds earlier than the epicentral time for the Tango earthquake. Likewise the first table which Hodgson published in the Bulletin of the Seismological Society of America in 1932 for the P-phase of the Tango earthquake gave times which, as he showed in a later paper published in the same Journal, were eleven seconds too great if the epicentral time was to be made the null-point, and nine seconds too great if the focal time were to be taken as the zero of reference. Hodgson chose to base his table rather on epicentral time than on focal time. Jeffries also chose epicentral time as the null-point for his recent tables.

However, beyond an epicentral distance of 10°, we think that it is more useful to tabulate the true travel-times. Hence we have adopted the focal time as the basis for our new Table. In order to avoid any ambiguity, we have decided to use the symbol T_E or simply E for the epicentral time and the symbol T_F or simply F for the focal time. The symbol F has been used in the international notation for the end of an earthquake-record, but this should cause no confusion. Where ambiguity would arise the word finis for the latter may be written out. A column headed (P-F) in the new Table signifies the interval between the focal time and the arrival-time of the P-phase. That interval is the true travel-time of P in an earthquake whose focal depth is comparable with that of the Tango and Hawke Bay earthquakes. An (S-F)-column, similarly, gives the travel-times for S.

As pointed out by Hodgson, a strong confirmation of the correctness of these travel-times throughout considerable ranges of epicentral distance is derived from the fact that, doubling the tabulated travel-time for half the distance and making proper allowances for the slight focal depth, we obtain almost perfect agreement with the observed reflections PR_1 and SR_1. A similar confirmation is obtained in the case of the later reflections. Hence we conclude that reflection occurs at the surface of the Earth and not, as some have thought, at a deeper discontinuity. Furthermore we may use this fact to check the correctness of less certain parts of the travel-time curves. The tabulated travel-times for the core-waves are based on Dahm's observations in the Hawke Bay earthquake. The entire Table, therefore, is derived from observation and is very nearly homogeneous.

The investigations of Hodgson and Dahm bring to our notice the very great improvement in timekeeping at seismographic stations throughout the world in the last few years. It now becomes possible to discuss with some prospect of success the differences in length of path and of consequent travel-times which are introduced by the equatorial bulge and the polar flattening of the Earth as well as by the relief of the Earth's surface. Dahm has found positive residuals for the reflected condensation-waves when the reflection occurs in the equatorial belt. He also mapped reflection-points in order to correct for relief and seems to find consistent differences between the travel-times for oceanic and continental reflection. For this purpose, however, much better maps of the ocean-bottom are needed. Gutenberg has called attention to another source of small differences. He thinks that the use of geocentric latitudes would give better results that the geographic or astronomic latitudes.

As stated before, the Table is valid only for shallow earthquakes, because the travel-times for deep-focus earthquakes are not only different, but bear no simple relation to the travel-times of shallow-focus earthquakes. We are confident that Father Brunner's investigation of the earthquake of May 26, 1932, which had a focal depth of 550 kilometers, will throw much additional light on this problem of deep-focus earthquakes. He is hopeful of evolving a method for determining both the focal time and the focal depth from the records of one station. If he is successful, his method will prove extremely useful in the determination of epicenters. In fact, Father Joliat has used Father Brunner's preliminary results with no small degree of success. Father Brunner hopes to make his method available in time for inclusion in the first volume of "Theoretical seismology" by Father Sohon and myself which is nearly ready for publication.

Mimeographed copies of the Table will be supplied gladly by the author to interested seismologists upon request.

In conclusion, I wish to thank all those directors of stations who kindly placed their seismograms at our disposal for study, Messrs. Hodgson and Dahm for their generous permission to use the results of their research, and finally those members of the staff of the Geophysical Laboratory of Saint Louis University who have generously assisted in the preparation and tabulation of the data for these tables, especially Messrs. Donald C. Bradford, Cornelius G. Dahm, and Robert Huber.

Geophysical Laboratory,
Saint Louis University,
Saint Louis, Missouri

SURFACE-REFLECTED WAVES OF SHALLOW-FOCUS EARTHQUAKES

Ernest A. Hodgson

(Abstract)

In the case of the seismological tables developed by seismologists during the first decade of the present century it was always assumed that the focus lay in the surface. Under such circumstances the so-called PR_1-wave, the wave once reflected at the surface at a point midway between the focus and the point of observation, would be expected to have a travel-time double that for the P-wave to the midpoint. Observation failed to support the earlier PR_1-tables which were constructed from the P-curves on this assumption.

It was later found that foci do not always, or even generally, lie in the surface. Furthermore, the P-curves for earthquakes of known shallow-focus are now found to differ considerably from the earlier curves based on group-data. It became desirable to study the travel-times for the once-reflected waves from the data of a single well-defined earthquake.

The seismometric study of the Tango earthquake, Japan, March 7, 1927, recently completed by the writer, furnished the opportunity for such a study, the results of which are presented in this paper.

This paper was presented before the Royal Society of Canada, May 19, 1933, at Kingston, Ontario; it is hoped the complete paper may be published in the Bulletin of the Seismological Society of America.

Dominion Observatory,
Ottawa, Canada

THE HUANCAYO SEISMOGRAPH-STATION IN PERU

J. A. Fleming

Since the report (J. A. Fleming, Bull. Seis. Soc. Amer., v. 22, 263-269, 1932) presented at the meeting of the Eastern Section of the Seismological Society of America May 2, 1932, on the seismological station at the Huancayo Magnetic Observatory, its site, building, and equipment, the instrumental equipment has been installed and the station is now in full operation.

The Observatory is in latitude 12° 02.7 south and longitude 75° 20.4 west in the valley of the Montaro River at an altitude of 11,000 feet above sea-level about 120 miles due east of Lima, Peru. Reference may be made to the previous report for a complete description of the Observatory's site, of the seismological building, and of the equipment.

Because of a delay in delivery of the two Wenner horizontal-component seismometers, they were not actually delivered at the Observatory until the first part of August 1932. The Wenner instruments and the Benioff vertical-component seismometer, together with their recorders, were installed and actual recording of the three components began August 22, 1932.

Records have been obtained without interruption since initiation of this work. There have, of course, been adjustments to the apparatus and some modifications in the optical arrangements to improve the records which were to be expected as a normal procedure in the establishment of a new station. Suitable magnification of about 2,000 is now being obtained for all three components. Higher magnification is not employed for the vertical component because of wind-effects. The reproduction herewith of the actual records for the north-south, east-west, and vertical components on January 18 Greenwich mean time, on which day there was a slight earthquake recorded, is a typical specimen of the character of the records being obtained. It will be noted that the microseisms recorded are about the average character for a station sufficiently removed from the coast so that continental conditions are encountered.

The records and the preliminary interpretations made by Dr. Cairns and his associates at the Observatory are forwarded promptly to Washington. When received, they

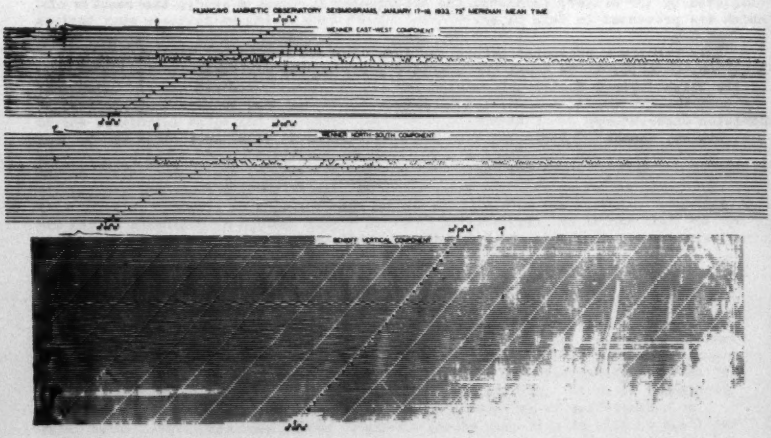

HUANCAYO MAGNETIC OBSERVATORY SEISMOGRAMS, JANUARY 17-18, 1933. 75° MERIDIAN MEAN TIME
WENNER EAST-WEST COMPONENT
WENNER NORTH-SOUTH COMPONENT
BENIOFF VERTICAL COMPONENT

Fig. 1--Huancayo Magnetic Observatory seismograms, January 17-18, 1933, 75th west meridian mean time

are turned over to the Division of Terrestrial Magnetism and Seismology of the United States Coast and Geodetic Survey for the compilations of that bureau. After the completion of these compilations they are to go to the Advisory Committee in Seismology of the Carnegie Institution of Washington for further detailed investigation. Already it is found that the seismograms from Huancayo are definitely useful for seismological investigation in Central America and in the location of epicenters in the Pacific Ocean off the west coast of South America, especially as regards the longitudes of epicenters in the northern portion of that area.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

GEOGRAPHICAL DISTRIBUTION OF DEEP-FOCUS EARTHQUAKES

V. C. Stechschulte, S.J.

The occurrence of earthquake-shocks at depths of three or four or even five hundred kilometers may, I think, be taken as well established, though the processes by which such shocks originate is not at all clear. It would also seem that the occurrence of such deep-seated shocks must be taken into account in our study of the character of the Earth's interior, as perhaps also in such problems as the depth of isostatic compensation and the like. It becomes of interest then to inquire if deep earthquakes occur only in restricted regions or whether they may be expected at any place.

In the International Seismological Summary for January, February, and March, 1927, published in 1930, the late Professor Turner wrote: "There have now been 141 cases of abnormally deep focus discussed in the summary and 17 cases of high focus. The latter are in several ways more doubtful in character ....., but there can be little doubt about the numerous cases of deep focus. Their positions have been plotted on a map and show a pronounced restriction to certain regions; most of them, and especially the deepest, seem to affect the boundary of an oval region about 180° long centered with fair accuracy on the equator, and including a considerable part of the Pacific Ocean, though its eastern boundary intrudes into South America. The suggestion has more than once been made that the moon came out of the Pacific Ocean; does this tolerably symmetrical curve indicate the scar which is even not yet quite healed?"

I suppose we have to admit that the curve thus drawn entails a rather generous amount of extrapolation and good will. The curve of course traverses what are well-known earthquake-zones, and we might not unreasonably expect deep shocks to occur, if occur they must, in the usual earthquake-regions. The question may, however, arise whether all the known zones are proportionately represented in the deep-focus class. At present this does not seem to be the case. I have plotted the epicenters of the quakes of 1918-29 to which focal depths of 0.025 to 0.09 R have been assigned in the Summary, together with a few other epicenters of the past year as given in the Saint Louis Preliminary Bulletins. No new light emerges from the results. Particular attention might be directed to the earthquake of May 21, 1932, centered at 24°75 south and 179°25 east which has been studied from the original records by Father Brunner at Saint Louis. He finds the focus at the tremendous depth of 550 km.

You will perhaps have noticed that in the reports from the Pasadena group of stations a notable number of the shocks are qualified as "deep." For many of these shocks, unfortunately, we shall probably never have an epicentral determination as they will hardly have been widely recorded. For several of the deep foci for which epicenters are given in the International Summary the number of stations for which arrival times are given is very small. It may happen in some of these cases that the epicentral distance of some of the stations may be quite large, while there is no report from other stations at equal or smaller distances. It may therefore be that we fail to have adequate records of many deep-seated shocks, and that the various "traces" of earthquakes we note on our records may in part at least be due to deep foci. This is only a guess, it is true, but the additional reputedly deep shocks recorded at Pasadena with the new Benioff vertical seismometer give some slight plausibility to the suggestion.

K. Wadati has studied during the past few years the deep-focus earthquakes occurring in and near Japan, and in his first paper speaks of a Deep Earthquake-Zone with a trend transverse to the main island of Japan. But in a later paper he finds at least one earthquake lying somewhat outside this zone. Wadati has published a map showing the earthquakes of 1926-27. On this map I have added the deep foci of 1928-31, again as given by Wadati in a later paper. There seems to be some sort of alignment of the deep foci, but further work is still needed.

It may be of interest in this connection to visualize by means of a rough scale drawing the significance of a focal depth of 350 or 400 kilometers. The diagram which was shown on the screen and reproduced from Scrase's recent paper, illustrated this.

By way of summary, I would say that in the light of the data available, we can scarcely make any assured generalization in regard to the distribution of deep foci, though they do not seem to be distributed entirely at random in the earthquake-belts. What the significance of this may be does not yet appear.

Xavier University,
Cincinnati, Ohio

WOOD-ANDERSON INSTALLATION AT BUFFALO

John P. Delaney, S.J.

(Abstract)

Through the kind generosity of Harry O. Wood and the manufacturers of the Wood-Anderson seismometer, Fred C. Henson Company, a long-period instrument was loaned to Canisius College for a study of building-tilt under the influence of solar radiation.

These tests were continued through the summer of 1932, but definite measurements of tilt due to solar heat revealed complications not attributable to this cause directly. The study was continued during winter months under conditions of artificial heating in the building, and it was found that even slight temperature-changes caused appreciable shifting of the zero. Whether this shift is due to building-tilt, or solely to a temperature-effect in the instrument, has not been determined.

Meanwhile the seismometer has been purchased for permanent installation, and it is hoped in the near future to complete the installation with the purchase of another long-period Wood-Anderson.

Canisius College,
Buffalo, New York

NEW RECORDING-VAULT OF THE HARVARD SEISMOGRAPH-STATION

L. Don Leet

(Abstract)

The Harvard seismograph-station, after 25 years of operation in the Geological Museum, Cambridge, is now housed in a new vault at Oak Ridge, Massachusetts, near Harvard and about 25 miles northwest of Cambridge. The coordinates of the station, determined astronomically, are 42° 30' 26" ± 1" north latitude and 71° 33' 45" ± 15" west longitude.

The new vault has been constructed as a unit of the research program directed by the Harvard Committee for Geophysical Research, and financed jointly by the Rockefeller Foundation and by friends of the Division of Geological Sciences at Harvard. The opening for the main room was excavated from solid rock, a Paleozoic micaceous schist, to a depth of over 15 feet. The room is 22 feet square inside. Two corners are occupied by small piers, and the main pier is an octagonal strip five feet wide. Its open center makes all parts readily accessible. The piers and floor were poured as a unit

with the underlying rock. An eight-foot covering of dirt renders the temperature in the vault practically constant; thorough waterproofing has prevented any infiltration of water; and calcium-chloride driers are proving entirely satisfactory for the control of humidity. A small work-shop adjoins the vault. A special dark-room is located in a separate building. A standard E. Howard pendulum-clock is used for timing. It is checked with NAA time-signals by means of a short-wave radio receiver. The clock is mounted in the main vault under optimum conditions. In the first three weeks of service its rate was reduced to one second per week, and it is expected this will be further improved.

The instruments will be two Milne-Shaw horizontal and two Wood-Anderson torsion horizontal seismometers, with a Benioff vertical recording by means of a short- and a long-period galvanometer. Special recording-drums, identical in design, are being used. Studies of New England microseisms, with special reference to direction of propagation, are being started. An investigation of semi-diurnal tilts recorded by the Milne-Shaws is planned, in addition to routine recording and the seismic surveying research which the station has been conducting.

Harvard University,
Cambridge, Massachusetts

RECENT AUXILIARY SEISMIC INSTALLATION AT WOODSTOCK COLLEGE, MARYLAND

John S. O'Conor, S.J., and John W. Tynan, S.J.

On January 1, 1932, an auxiliary seismic station was opened at Woodstock College, Maryland, under the auspices of Georgetown University. The installation comprises a pair of Bosch horizontal pendulums, with photographic recording. The primary purpose of the establishment of the station is to train observers to supply the personnel required for replacement and expansion in the Jesuit observatories along the Eastern Seaboard.

This station will serve as a cooperative unit with Georgetown, by supplementing, with its machines of lower magnification, the records from the highly sensitive Galitzins in Washington. Information on all major earthquakes is sent to the Jesuit Seismological Association.

The instruments are mounted on a concrete pier, laid in clay, and are operated at a period of 8 seconds with critical damping. Magnification is slightly over 100. Time-marks, accurate to one second, are provided by a Spindler Hoyer contact-clock, corrected thrice daily by comparison with Arlington. All records, since the inception of recording, are kept on file and are available to those interested in making investigations which require a study of the original seismograms.

Woodstock College,
Woodstock, Maryland

THE TECHNOLOGY SEISMOGRAPH-STATION

George L. Hosmer

After long delays in securing the instrumental equipment, the Technology Seismological Station was put in operation July 5, 1932. This seismograph is on the grounds of the Surveying Camp operated by the Massachusetts Institute of Technology, and is just north of United States Route 1, on Gardner Lake, about six miles east of Machias, Washington County, Maine. The equipment consists of two horizontal components of the Wenner seismometer, mounted on a low concrete-pier about four feet by six feet, resting on an outcropping ledge. The building is of concrete with enclosed airspace on the walls and ceiling, and also on the roof. The room is entered through two outer rooms. The walls are banked with earth up to the eaves. The rather serious moisture-difficulties encountered at first now appear to have been overcome.

An underground cable about 900 feet long connects the seismometers with the recording-room, which is in the cellar of the caretaker's house. In the recording-

room are the two galvanometers, the recording-drum, the timing-clock, and a short-wave radio set. The recorder is an American Instrument Company product; the timing-clock is a Seth Thomas wall-clock. Adjoining the recording-room is a small developing-room, which also serves as an entrance to the recording-room.

The instrument is operated by E. O. Dennison, the caretaker of the Camp. Records are sent immediately to the office of the United States Coast and Geodetic Survey. The minor difficulties incident to the operation of a new station appear to have been met successfully and the records are quite satisfactory. It remains to be seen what the effect on the records will be when the ice breaks up on the lake in the spring, as well as the microseisms traceable to the location near the coast in a region where the seas are sometimes exceedingly rough.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

THE UNIVERSITY OF VERMONT SEISMOGRAPH-STATION

Elbridge C. Jacobs

The University of Vermont Seismograph Station was made possible by the building of the Fleming Museum, a grant from the National Research Council for the instruments, and the cooperation of the University authorities in providing the vault, operating expenses, etc.

The station occupies an underground vault, 25 feet east of the Museum with which it is connected by an underground passage. The Museum is well separated from other buildings and stands about 250 feet from Colchester Avenue on which it fronts. It is 231 feet above Lake Champlain.

Geology of the site--The University buildings stand upon the Lake Champlain fault ("Logans Line") of lower Cambrian quartzite and dolomite thrust northwestward into Ordovician (Trenton) limestone. The University Campus, on the northern border of which the Museum stands, is made up of four or five feet of glacial gravel underlain by an unknown depth of very compact blue glacial clay carrying boulders of various sizes. The denseness of the clay is so great that a 15-foot bar driven into the ground by a jack-hammer could not be withdrawn even by sizable jacks.

The seismograph-vault--The vault is 12.5 feet by 9.5 feet by 10 feet high, with the roof sunken two feet below the surface. The long axis strikes due northwest, at an angle of 45° with the east wall of the Museum. The vault is of reinforced-concrete construction with 10-inch walls, waterproofed on the outside, tiled and drained into the sewer which passes near one corner. An uptake, provided with an exhaust-fan, in the roof, and grated doors at either end of the underground passage will, it is hoped, keep the vault dry during the humid months; in winter the uptake is tightly closed and the vault has been found quite dry. A duct electric heater, with thermostat, keeps the temperature quite uniformly between 60° and 62° F. The vault and the instrument-lamps are lighted by electricity.

The pier--The pier is a monolith of unreinforced concrete, 6 feet by 8 feet by 7 feet 2 inches deep, set 13 inches into the underlying clay (Figure 1). It stands 30 inches above the floor from which it is separated by a 6-inch "moat." It is oriented true northwest and northeast. Its latitude is 44° 28' 48".3 north, its longitude is 73° 11' 49".7 west, and its elevation is 326.9 feet above mean sea-level.

The instruments--The station is equipped with two Milne-Shaw horizontal-component seismographs, serial Nos. 52 and 53, made by J. J. Shaw at East Bromwich, England, in 1932.

Instrumental constants--The instrumental constants are: Mass, 2.2 kg; magnification, 250; free period, 12 seconds; magnetic damping, damping-ratio 20/1; sensitivity, 50.9 on northwest and 43.35 on northeast; paper-speed, 8 mm per minute.

Greenwich time is maintained by means of a Seth Thomas clock equipped with a mercury, second-pendulum, and a specially designed electric contact actuating a relay

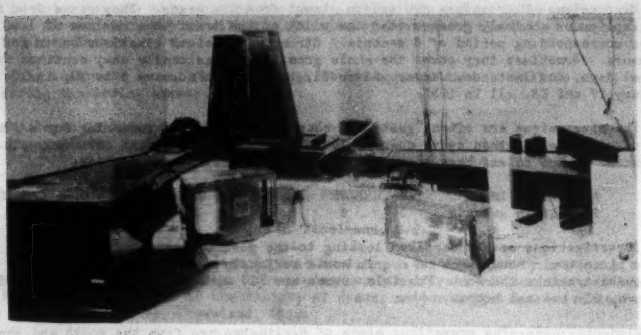


Fig. 1--Pier-top with instruments

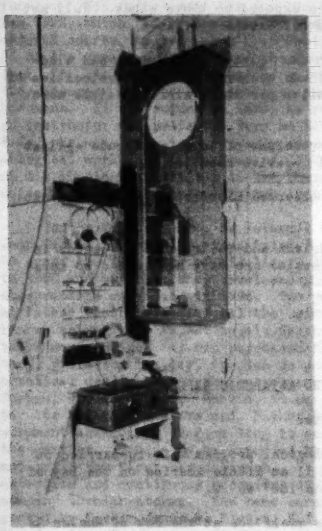


Fig. 2--Time-control equipment

which in turn operates the shutters in the seismograph lamps (Figure 2). The clock is located in the vault (Figure 2) and is checked with Arlington time by means of an Atwater Kent radio set. Between December 27, 1932 and April 1, 1933, the clock gained one second.

The station is equipped with a barograph and a thermograph. There is ample room on the pier for a vertical component which, it is hoped, may ultimately be obtained.

Performance--The performance of the seismographs is, on the whole, satisfactory. The pier is so stable that its tilt is slight. Tilt-tests have shown a maximum of about 1.5 seconds of arc. The travel-lines on the grams have never fouled. The grams are remarkably clear except in cases of waves of large amplitude being recorded when they sometimes become indistinct. It is thought that a more rapid paper would rectify this fault. The paper in use is made by the Haloid Company of Rochester, New York.

The weak point in the instruments is the clock-drive for the recording-drums. The clocks are not well made, with the result that, especially on the northwest component, the hour intervals do not form a straight line but frequently curve considerably and varyingly. It follows that the different phases do not always appear at respectively simultaneous times on the two grams. A gravity-drive would apparently be a great improvement.

The station went into commission in November 1932. Since then it has recorded all of the earthquakes located by the Coast and Geodetic Survey and several others.

Personnel and routine--The station is operated by the seismologist, and two Museum assistants who change the grams, develop them, etc., etc. Grams are changed at 5 p.m. The clock is checked against Arlington time almost daily at noon. Earthquake-data are transmitted to the Coast and Geodetic Survey.

Microseisms--Microseisms are seldom absent from the grams. They range from minimum amplitudes scarcely greater than the width of the trace to a maximum of 1.45 mm with a corresponding period of 8 seconds. Strong microseisms sometimes occur for a few hours. Sometimes they cover the whole gram, and occasionally they continue for several days, for instance, January 26 to 31, inclusive, February 6 to 10, inclusive, February 27 and 28, all in 1933.

The microseisms are often "gusty" in character, the gusts occurring for a fraction of a minute and then dying down, only to wax again in the next interval, etc. The maxima of the seisms have given the following amplitudes and periods:

Amplitudes in mm	1.45	1.25	1.1	1.0	0.95	0.90	0.85	0.80
Periods in seconds	8	6	6	5	5	5	5	7

Investigations were undertaken looking to the possible cause of these microseisms since their occurrence on a gram would seriously mask the appearance of earthquake-tracings thereon. Possible causes are (1) wind-pressure, (2) barometric pressure, (3) coastal storms.

Wind-pressures--The prevailing winds of Burlington are from the south and they are often strong and gusty, attaining a velocity of 40 or more miles an hour. The University buildings, located on high ground, are exposed to these winds. Full meteorological data are available at the nearby Federal Weather Bureau.

There was found to be no connection between the "gusty" microseisms and wind-velocities; for example, seisms of maximum amplitude occurred with wind-velocities of 18 miles per hour, while with velocities of 29 miles per hour, minimum seisms were noted.

Barometric pressures--A checking of the microseisms of large amplitude against periods of barometric "highs" and "lows" yielded negative results.

Coastal storms--This possible cause of the observed microseisms will be investigated.

It is recognized that the subject of microseisms and their cause or causes is not new, while the Burlington Station and its operator are very new indeed to seismology.

University of Vermont,
Burlington, Vermont

THE SEISMOLOGICAL PROGRAM OF THE BYRD ANTARCTIC EXPEDITION II

Thomas C. Poulter

Conditions permitting, the following seismological program will be carried on during the stay of the Byrd Antarctic Expedition II at Little America on the Bay of Whales, Antarctica. Latitude 78° 34' S, longitude 163° 45' W.

It has been rather definitely shown that the shelf ice at the Bay of Whales is not floating, but rests on the underlying rock. For this reason it is believed that, if a shaft is sunk down through the snow to the surface of the ice and the recording seismometers mounted on piers frozen into the ice, fairly good results should be obtained. A clock-driven recorder will be used, having two drums each 12 inches in diameter and 24 inches long. This recorder is adjustable as to the rate at which the drums move endwise so that from three to seven days' record can be obtained on the same sheet of bromide paper.

Two McComb-Romberg type seismometers will be used for this work and six similar instruments modified for use as tilt-meters will be used for studying tilting effects of the ice. The tilt-meters will make a 30-day continuous record without attention.

In order to make this work of the greatest possible value, it is planned to keep a fairly close radio contact with the Division of Geodesy of the United States Coast and Geodetic Survey.

This equipment is well under way and it is expected that it will be ready to test out during the coming summer.

Iowa Wesleyan College,
Mount Pleasant, Iowa

MEMORIAL TO THE REVEREND FREDERICK L. ODENBACH, S.J.

James B. Macelwane, S.J.

On March 15, 1933, the Seismological Society of America lost by death one of its early members who for many years held a place on its Scientific Committee, the Reverend Frederick L. Odenbach of the Society of Jesus, meteorologist and seismologist of John Carroll University, Cleveland, Ohio.

Father Odenbach was born in Rochester, New York, October 21, 1857, the son of a furrier. His father sent him for his college education to Canisius College, Buffalo, New York, which had been opened by the German Jesuits not long before. After a successful course, he graduated from Canisius College in the spring of 1881. September 26 of the same year he entered the Society of Jesus and was sent to Blijenbeck, Holland, for his novitiate. Remaining in Europe for graduate-studies in philosophy and the sciences, he came into intimate contact with the noted biologist, Father Eric Wasmann. In the summer of 1885, he returned to his Alma Mater, Canisius College, as an instructor and prefect. Here he had as his assistant Brother George E. Rueppel, S.J., who was later to be closely associated with him in his meteorological and seismological work. In the summer of 1887, he was again sent to Europe--this time to take up his theological studies in the Seminary at Ditton Hall, England, where he was ordained to the Catholic priesthood in the summer of 1890.

In the fall of 1892, he returned to America and was assigned to the faculty of John Carroll University, then Saint Ignatius College, Cleveland, Ohio, where he was to spend the remainder of his life. Brother George Rueppel followed him to Cleveland in 1894 and together they developed plans for a meteorological observatory. The first observations were made in 1896. Two years later, the Smithsonian Institution placed at Father Odenbach's disposal the universal meteorograph which had been built by the famous astronomer, Father Angelo Secchi, S.J., for the Paris Exposition and which had there won a prize. It was purchased for the Smithsonian Institution; but the Secretary, Professor Langley, foresaw no possibility of putting the Secchi meteorograph to practical use in Washington. At the suggestion of the present Director of the Weather Bureau, Professor C. F. Marvin, it was offered to Father Odenbach. In three days after its arrival in Cleveland, Father Odenbach had the large and very complicated instrument assembled. Before long it was ready to record all the principal elements of the weather. Gradually he expanded the meteorological equipment. In 1899, he devised and built the first ceraunograph. It was an adaptation of the Branly coherer to the detection and continuous recording of the static disturbances which precede and accompany thunder-storms. The name ceraunograph which is now in general use was suggested by Father James A. Kleist, S.J., who was then a colleague of Father Odenbach on the faculty of John Carroll University. At the urgent suggestion of Brother Rueppel, Father Odenbach, in 1900, designed and built his first seismograph, utilizing the principle of the horizontal pendulum with the Hengler-Zöllner type of suspension. A little later he also built and mounted in the basement of the college an electric seismograph which was in effect an accelerograph. It consisted of a heavy vertical pendulum surrounded by four insulated carbon-contacts or microphones, corresponding to the four cardinal points, whose four parallel circuits were led up to his Observatory offices in the tower of the College, where they operated a recording-mechanism. In 1901, Brother Rueppel was transferred to Saint John's College, Toledo, Ohio, where he in turn built up a meteorological observatory. Thus, Father Odenbach was left alone at John Carroll.

In the succeeding years, Father Odenbach conceived a plan for more widespread investigation in seismology. The opportunity presented itself when the smaller Wiechert

seismograph was placed on the market at a very reasonable price by Spindler and Hoyer in Göttingen, Germany. February 2, 1909, he addressed a letter to all of the colleges and universities under the administration of the Society of Jesus in the United States and Canada, calling their attention to the scientific possibilities in the seismological field and recommending that the small Wiechert seismograph be adopted as the standard instrument in a widespread Jesuit Seismological Service. As a result of his enthusiastic sponsorship, the plan was adopted by 16 colleges and universities, and 18 of these seismographs were imported into the United States and one into Canada in the course of the next two years. Although, through no fault of Father Odenbach, the organization which he formed for cooperation was short-lived, the stations which were then established continued for the most part to do excellent scientific work, in so far as changes of administration and personnel permitted. Father Odenbach is therefore to be considered the founder and father of Jesuit seismological activity in the United States.

In the meantime, however, the location of his own station in west Cleveland became less and less desirable because of the increase of city traffic in the neighborhood. The local disturbances eventually became so bad that it was no longer possible to obtain good records. Father Odenbach then reluctantly dismantled his seismographs, keeping only one in operation for the sake of the qualitative results it could furnish, and began to lay plans for a new station where his instruments would not be disturbed. The new campus of John Carroll University at University Heights seemed to him to offer splendid possibilities. Accordingly, his plans for a meteorological and seismological station were incorporated in those of the buildings. When construction was begun as the result of a city-wide canvass for funds, Father Odenbach was jubilant. In the summer of 1932 the work was so far advanced that he packed up his meteorological and seismological equipment and transferred it to the new site. In the course of the autumn, however, it became clear that, on account of the continued depression, funds would not be available for the completion of the buildings. Nevertheless, Father Odenbach began to set up his instruments as best he could, in the meantime living in his future office-quarters on the new campus. However, this strenuous life was too much for his advanced age and he was obliged to return to the community in the early winter. His health steadily failed and an operation was found necessary. After the operation, he was very cheerful with all those who visited him in the hospital, and everyone thought he was on the way to recovery when a sudden collapse occurred and he passed away March 15, in the 76th year of his age.

In Father Odenbach, John Carroll University has lost one of the best known and most beloved members of its faculty, a scientist whom 40 years of continuous service as director of the Angelo Secchi Observatory had made familiar to all Cleveland. In him the Seismological Society of America has lost an enthusiastic member; and the Jesuit Seismological Association has lost the man who was primarily responsible for the country-wide effort which it represents.

Geophysical Laboratory,
Saint Louis University,
Saint Louis, Missouri

REVIEW OF SEISMOLOGY IN THE UNITED STATES

N. H. Heck

The year has been an active one in all branches of seismology in spite of the unfavorable economic conditions. A review of the accomplishment of the Coast and Geodetic Survey will first be given, then a synopsis of the work of other organizations so that the first may be seen in its proper relation.

Coast and Geodetic Survey

The seismological work of this Bureau covers the entire United States and the regions under its jurisdiction, except that the Philippine Government has its own organization for this work. The work is more intensive and the direct utilitarian application is greater in the regions where earthquakes are of such character as to involve danger to life and property. There are three principal branches of the work:

(1) The collection of information in regard to the visible and felt effects of earthquakes; (2) the operation of teleseismic instruments; and (3) the operation of instruments for recording the full strength of earthquake-motions.

During the past year the collection of earthquake-reports has become fully standardized and though further expansion might be desirable it is not practicable for economic reasons. The number of reporters is already in the thousands. The plan is cooperative throughout but is especially effective in the Pacific Coast Region. At first thought this information might not appear to have the same scientific importance as instrumental records. However, it has been found that while men can not duplicate the machines in accuracy, on the other hand the machines can not give the information that men can. Besides in many cases the earthquake is not felt most strongly immediately over the instrumental epicenter and there are many other anomalies so that instrumental records and reports of visual observations must be combined to get the full story. The reports are studied not only at Washington but at the University of California at Berkeley, California, at the Seismological Research Laboratory at Pasadena, and for the Middle West at St. Louis University, St. Louis, Missouri.

The teleseismic work of the Coast and Geodetic Survey is largely cooperative, or if carried on by the Bureau alone is confined to regions where there is no other agency at work. There are eight stations at which the Bureau operates alone or cooperatively. In addition, the records of six other stations are interpreted by the Coast and Geodetic Survey. These stations are listed in the Table below. The principal aim is to obtain the most accurate possible epicenters of earthquakes in which the United States is directly interested. During the year there were 41 earthquakes of sufficient intensity so that immediate determination of the epicenter was practicable and important. Independent determination is also made by the Jesuit Seismological Association. This information, in addition to furnishing information to those interested, is useful to the individual stations in interpreting their records. Particular attention is given to the study of earthquake wave-transmission since on this depends the accuracy of the determination of epicenters.

Three types of instruments are now in use in recording strong earth-motions--accelerographs, displacement-meters, and Wood strong-motion instruments. The first made useful records of the southern California earthquake of March 10, 1933, and a number of the others have been installed. Details are being given in a paper by H. E. McComb.

The Coast and Geodetic Survey has carried out some triangulation and also run precise-level lines in regions subject to earthquakes. Some of this work was in the region of the earthquake of March 10, 1933. Precise-level lines are also being run in the region of the Nevada earthquake of December 20, 1932.

Work of other organizations

The Jesuit Seismological Association, with headquarters at St. Louis, Missouri, has associated with it 12 stations at various universities which are active at the present time and two which are temporarily inactive. These are all listed in the Table below. At 11 other universities throughout the United States, seismographs of modern type are in operation. The local investigation in southern California and in the San Francisco Bay Region, under the auspices of the Carnegie Institution of Washington, the California Institute of Technology, the University of California, and Stanford University, is well organized, and various methods are being used. Remarkable accuracy of epicenter-determination is becoming possible. Similar activity is being carried on by St. Louis University in the Mississippi Valley Region, which has been aided by the National Research Council. Much work has been done in the engineering field which has resulted in reduced loss from a recent earthquake and similar reductions are probable in the future.

There has been considerable interest in the study of the geology of oceanic basins during the year, especially in the West Indies-Caribbean region, and the American Geophysical Union has a strong committee which deals with this subject. The earthquake-studies are of importance and these have been greatly aided by the installation during the past year of modern instruments at Balboa, Canal Zone, at the Huancayo Magnetic Observatory of the Carnegie Institution of Washington, and by Father Sarasola at Bogotá, Colombia.

The earthquakes of the year will be discussed by another speaker. The only ones of particular interest within the United States are the Nevada earthquake of December 20, 1932, and the southern California earthquake of March 10, 1933. Otherwise, the year was a rather quiet one.

The following list of stations is given for reference, and it is hoped that any corrections will be furnished.

Table 1--List of active seismological stations

Place	Organization	Records interpreted by	Modern instruments
Technology, Me.	Mass. Inst. of Technology	Coast and Geodetic Survey	Yes
Burlington, Vt.	University of Vermont	University of Vermont	Yes
Cambridge, Mass.	Harvard University	Harvard University	Yes
Weston, Mass.	Weston College	Jesuit Seismological Asso.	No
New York, N. Y.	Fordham University	Fordham and Jesuit Seis.Asso.	Yes
Buffalo, N. Y.	Canisius College	Canisius and Jesuit Seis.Asso.	Yes
Pittsburgh, Pa.	University of Pittsburgh	Coast and Geodetic Survey	Yes
Woodstock, Md.	Woodstock College	Woodstock and Jes. Seis. Asso.	No
Washington, D. C.	Georgetown University	Georgetown University	Yes
Charlottesville, Va.	University of Virginia	Coast and Geodetic Survey	Yes
Columbia, S. C.	Univ.of S.C. and CGS	Coast and Geodetic Survey	Yes
Cincinnati, Ohio	Xavier College	Xavier and Jesuit Seis. Asso.	Yes
Chicago, Ill.	CGS, USWB, Univ.Chicago	Coast and Geodetic Survey	Yes
St. Louis, Mo.	St. Louis University	St.Louis Univ. and Jesuit S.A.	Yes
Florissant, Mo.	St. Louis University	St.Louis Univ. and Jesuit S.A.	Yes
Little Rock, Ark.	St. Louis Univ. and NRC	St. Louis University	Yes
Madison, Wis.	University of Wisconsin	University of Wisconsin	Yes
Ann Arbor, Mich.	University of Michigan	University of Michigan	No
Denver, Colo.	Regis College	Regis College and Jesuit S.A.	No
Denton, Tex.	John.W. Crain	John W. Crain	Yes
Tucson, Ariz.	Coast and Geodetic Survey	Coast and Geodetic Survey	Yes
Bozeman, Mont.	Mont.State Coll. and CGS	Coast and Geodetic Survey	Yes
Spokane, Wash.	Gonzaga College	Gonzaga and Jesuit Seis.Asso.	No
Seattle, Wash.	University of Washington	Coast and Geodetic Survey	No
Ukiah, Calif.	Coast and Geodetic Survey	Coast and Geodetic Survey	Yes
Mineral, Calif.	U.S. Geological Survey	U. S. Geological Survey	Vol.[1]
Berkeley, Calif.	University of California	University of California	Yes[2]
Santa Clara, Calif.	Santa Clara University	Santa Clara and Jesuit S.A.	Yes
Pasadena, Calif.	Carnegie Inst. of Wash. (Cal. Inst. of Technology)	Seismological Research Lab.	Yes[3]
San Juan, P. R.	Coast and Geodetic Survey	Coast and Geodetic Survey	Yes
Balboa, Canal Zone	Canal Zone	Canal Zone	Yes
Sitka, Alaska	Coast and Geodetic Survey	Coast and Geodetic Survey	Yes
Honolulu, T. H.	CGS and Univ. of Hawaii	Coast and Geodetic Survey	Yes
Hawaii, T. H.	Volcano Observatory	Volcano Observatory	Vol.[1]
Agana, Guam	Govt.of Guam	Manila Observatory	No
Manila, P. I.	Manila Observatory	Manila Observatory	Yes[4]
Huancayo, Peru	Carnegie Inst. of Wash.	Coast and Geodetic Survey	Yes
Montezuma, Chile	Smithsonian Institution	Coast and Geodetic Survey	No

[1] Vol. = volcanological. [2] Two subsidiary stations. [3] Six subsidiary stations. [4] Three subsidiary stations.

Stations having instruments, none modern, which did not operate during the year include: New Haven, Connecticut, Yale University; Chicago, Illinois, Loyola University; Ithaca, New York, Cornell University; Cleveland, Ohio, John Carroll University; Worcester, Massachusetts, Holy Cross College; Spring Hill, Alabama, Spring Hill College; Reno, Nevada, University of Nevada; New Orleans, Louisiana, Loyola University; Lawrence, Kansas, University of Kansas; Salt Lake City, Utah, University of Utah; Milwaukee, Wisconsin, Marquette University; Point Loma, California, Theosophical University.

It may be of interest to note that in 1920 there were 33 seismological stations in the United States, 15 of which either no longer exist or, if they have instruments, are not operating them. Of the remaining 18, 13 have new instrumental equipment or have made fundamental changes in the old. It will be seen that very real progress has been made and that there is an excellent basis for seismological work in the United States, much of which should survive the difficulties due to economic conditions. Recent additions to the list of stations are the University of Vermont at Burlington, Vermont, and the Massachusetts Institute of Technology at Technology, near Machias, Maine. Outside of the United States, but with funds supplied from this country, are those at Huancayo, Peru, which has been mentioned, and that at Montezuma, Chile, the solar-radiation station of the Smithsonian Institution.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SEISMOLOGICAL WORK AT GEORGETOWN UNIVERSITY

F. W. Sohon, S.J.

Apart from keeping up to date with the routine work, other seismological activities at Georgetown are necessarily spasmodic. We had the courage to reopen the bundles of old records, and to attempt to make these accessible by filing them in chronological order. The work has not as yet been completed. We have records for every year back to and including 1911, but how complete the records are we cannot tell. Many of the records are in very poor condition. Our catalog of readings only goes back to 1925, though the readings of the nine preceding years are preserved in the nine printed annual reports for the years 1916-24.

Following a suggestion made by a committee of the Eastern Section of the Seismological Society of America to consider simplifying the monthly instrumental bulletins, the Georgetown Instrumental Bulletin was modified in May 1930, so as to supply a model report embodying proposed changes. It is not necessary to enumerate the changes here. The question to be decided is whether a return should be made to the sexagesimal system. As long as it is advisable that the Georgetown report should serve as a model report, a change should not be made. We have been presenting these reports for three years, and so perhaps a model is no longer necessary. In that case it might be well to return to the less satisfactory sexagesimal system for the sake of uniformity. An entirely different question then arises as to whether we should continue to keep our own records in the decimal system. Certainly until we get special scales that read directly in the sexagesimal system it will be much easier to do our own work in the decimal system, and convert the results to the sexagesimal system for the reports.

With regard to the instruments, there seem always to be repairs and adjustments to be made. We have just finished replacing the lower hinge on the Mainka east-west component, and now the clock-work on the Wiechert has taken a rest. The gears are badly worn and will have to be replaced. Then as mentioned in our Bulletin, the magnets on the vertical Galitzin have been growing weaker, so that we are no longer able to secure critical damping. The zero of the G-N galvanometer wanders badly. The automatic recording of time-signals has given no trouble since last August when a transformer burned out and had to be replaced. The system of light-intensifier and signal designed by Father O'Conor, although it works well enough, has not been kept in operation because the auxiliary lamp is not satisfactory.

There are also a number of unfinished problems in the Office. One of several may be mentioned. It seems that the turning points on the horizontal components of the sinusoidal microseisms are actually simultaneous. This suggests that the azimuth of the orbit of the Earth-particle be studied. In the few cases we have studied the azimuth seems to be quite steady. We should like to know whether this azimuth changes with meteorological changes. Unfortunately our instruments are badly influenced by wind, and by the students going up and down stairs, so that this is just another unfinished problem.

Georgetown University,
Washington, D. C.

THE TRAVEL-TIMES OF THE P- AND S-WAVES FROM MEXICAN EARTHQUAKES

Dean S. Carder

A recent study of the larger world-shaking earthquakes since 1910 has led me to question the accuracy of many of the established Mexican epicenters. In particular, many of the epicenters of Mexican earthquakes given in the preliminary reports of the Jesuit Seismological Association and the United States Coast and Geodetic Survey seemed to be in error in such a way as to tend to place these quakes from one to three or four degrees too far to the south. Errors of this kind which are consistently in the same direction could easily arise through the combination of certain circumstances, two of which seem to apply here: (1) Errors in the (S-P) tables, and (2) the grouping of all stations upon which determinations are based on the same side of the disturbance.

Data from South American stations are not included in the reports of the Jesuit Seismological Association or the Coast and Geodetic Survey; hence these organizations have no southward control in their location of Mexican epicenters. The shifting of an assumed epicenter a few degrees north or south due to errors in the (S-P) tables would not seriously impair the consistency of the results derived from the data used, these being for the most part from the American stations. I shall illustrate this later.

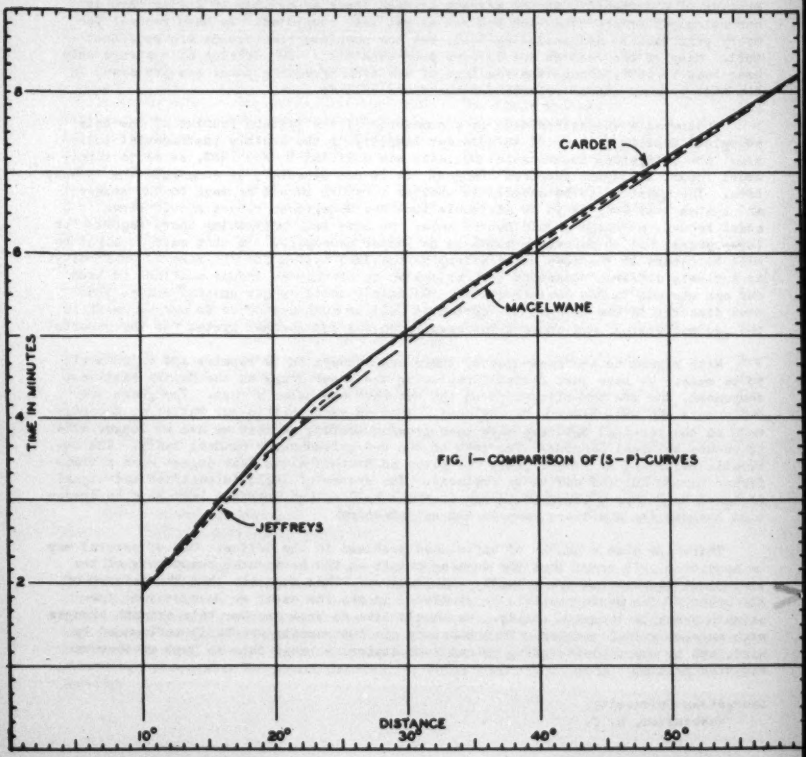


FIG. 1—COMPARISON OF (S-P)-CURVES

In an attempt to correct these errors, all available reports from South American stations were used, especially those from La Paz, for the times as given by that station are consistently accurate. Byerly's P-curve for the Montana earthquake was chosen since it is based upon an American earthquake and since it closely agrees with his P-curve for the Texas earthquake. Similar results could have been obtained from any of the established travel-time tables for P, especially for the Central American quakes, as the distances from the North and South American stations are about the same. The (P-O) method was used, but in order to arrive at consistent results, it was found necessary to shift many of the established epicenters northward through distances of one, two, or three or more degrees. An example is cited:

The Coast and Geodetic Survey located the earthquake of March 21, 1929, at 12° north and 90° west, and the Jesuit Seismological Association located it at 11° north and 90° west. Using the Jesuit Seismological Association epicenter, the time of occurrence was $2^h\ 36^m\ 43^s$ U.T., with residuals of ± 2 seconds or less for the North American stations, and $2^h\ 37^m\ 10^s$ with residuals of ± 2 seconds or less for the South American stations. The corrected epicenter is 13°9 north and 90°5 west, and the time $2^h\ 36^m\ 58^s$ with residuals no greater than 3 seconds for all stations used. This is a shift of three degrees north and a little west from the Jesuit Seismological Association location and of two degrees from the Coast and Geodetic Survey location. All of the other relocations that were made were, without exception, northward. The reason seems obvious. The established (S-P) tables are such as to tend to give epicentral distances which are too great. It appears, then, that revised (S-P) tables are necessary for a proper preliminary location of many of our Mexican earthquakes.

With this object in view, I selected 18 representative Mexican earthquakes, which are listed in the following Table together with their corrected epicenters and times of occurrence.

Table 1--Representative Mexican earthquakes, 1916-32

Date	Region	Epicenter		Time of occurrence		
		Lat. N	Long. W			
		°	°	h	m	s
Nov. 21, 1916	Oaxaca	15.2	95.8	6	25	30
Dec. 29, 1917	Oaxaca	15.1	96.4	22	50	24
Apr. 17, 1919	Guatemala	15	91.7	20	53	00
Feb. 4, 1921	Chiapas	16	92.8	8	22	30
Mar. 28, 1921	Honduras	12.5	87.3	7	49	14
May 1, 1921	Colima	19.2	104.2	5	39	03
July 7, 1925	Colima	19.6	106.5	14	12	21
Nov. 16, 1925	Colima	18.5	107	11	54	54
Aug. 20, 1927	Panama	5	82	23	54	24
Mar. 22, 1928	Oaxaca	16	96	4	16	54
June 17, 1928	Oaxaca	16.2	96.2	3	19	22
Aug. 4, 1928	Oaxaca	16	98	18	26	10
Oct. 9, 1928	Oaxaca	16.7	97	3	01	06
Mar. 21, 1929	Guatemala	13.9	90.5	2	36	58
Aug. 17, 1929	Oaxaca	17.4	98.6	23	40	45
Jan. 2, 1931	Colima	19.5	107.3	9	48	58
Jan. 15, 1931	Oaxaca	16.6	96.5	1	50	38
Dec. 7, 1932	Zacatecas	21.1	103.9	16	22	19

Data as given in the various station bulletins were used, and the travel-times of the tabulated P- and S-waves were plotted against the corresponding epicentral distances. Measurements were made on an accurate 37-inch globe. P- and S-curves agreeing with the largest number of plotted points were drawn and the differences in their ordinates were used to form the (S-P) curve as shown by the solid curved line in Figure 1. The P-curve agrees closely with Byerly's Montana curve, as was to be expected, since the Montana curve was used in making the relocations. The larger number of data used were for epicentral distances of from 20° to 60°. The portion of the curve between 10° and 20° is tentative. Figure 1 compares the new (S-P) curve with those taken from Jeffreys' and Macelwane's tables. The greatest departure is seen to be in the region of 23°, the average distance of many of the stations that are used to locate Mexican epicenters.

I have tested the new curve on several of the large North American earthquakes not used in its construction. Epicenters obtained through its use seem to lie fairly close to those obtained by the (P-O) method for earthquakes of Central America, the Oaxaca Region, the Gulf of California Region, and the United States. It also seems to apply for the Alaskan and Aleutian Island quakes. It apparently fails for quakes of the Colima Region--in particular for those of June 1932, though arcs based on its use pass closer to the probable epicenter than do most of the arcs based on the older tables. The Berkeley records for the Colima quakes of June 3, 18, and 22, 1932, show a distinct impetus following the first arrival of a weak P-wave by about 20 seconds. Many other stations report a similar appearance, some reporting the impetus as the first arrival. The reported S-waves appear to belong to the second impetus rather than the first emersio. For quakes centering in the Colima Region, many records show a second arrival following the first by 15 to 25 seconds; it appears that one may come closer to the correct epicenter should the second arrivals be used to get the (S-P) intervals and then the corrected intervals be applied with the new curve.

Table 2--Table for the (S-P) interval for epicentral distances between 10° and 60°

Distance	(S-P)	Distance	(S-P)	Distance	(S-P)	Distance	(S-P)
°	m s	°	m s	°	m s	°	m s
10	1 54	23	4 13	35	5 37	48	7 00
11	2 05	24	4 20	36	5 44	49	7 06
12	2 16	25	4 28	37	5 51	50	7 12
13	2 28	26	4 35	38	5 57	51	7 18
14	2 39	27	4 42	39	6 03	52	7 24
15	2 50	28	4 49	40	6 10	53	7 30
16	3 01	29	4 56	41	6 17	54	7 36
17	3 12	30	5 04	42	6 23	55	7 42
18	3 24	31	5 11	43	6 29	56	7 48
19	3 35	32	5 17	44	6 35	57	7 54
20	3 46	33	5 24	45	6 41	58	8 00
21	3 56	34	5 31	46	6 47	59	8 06
22	4 05	35	5 37	47	6 53	60	8 12

The new curve was tested by locating the epicenter of the recent Long Beach earthquake. The data published by the Jesuit Seismological Association were used, and with only one exception--Ann Arbor, for which the arcs were far off for all the tables--the arcs obtained fell reasonably close to the epicenter as located by Pasadena (which epicenter agrees well with the center of destructive effects), while the tables of Jeffreys and Macelwane both put the arcs too far out to sea. This result is interesting in that the new (S-P) curve was constructed independently of any data from the Long Beach earthquake.

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ANALYSES OF RATES OF ROTATION OF RECORDING-DRUMS

A. Blake and H. E. McComb

In a paper presented at the Stockholm conference of August, 1930, on the Wood-Anderson seismograph (Publications du Bureau Central Seismologique International, Série A, Travaux Scientifiques, Fascicule No. 7, pp. 80, 86), Macelwane makes a comparison of irregularities in the rates of rotation of recording-drums by studying the changes in length of the minute-intervals. A method used by the Coast and Geodetic Survey in testing recorders is described by McComb in the March, 1932, issue of the Bulletin of the Seismological Society of America. The method consists in flashing time-marks on the drum, as it rotates, at shorter intervals than are to be used in normal operation of the recorder. This paper contains an analysis of results obtained by this method on seven seismograph-recorders, as follows: (1) Honolulu Observatory Milne-Shaw clock-driven recorder, north-south component; (2) Honolulu Observatory Milne-Shaw clock-driven recorder, east-west component; (3) Sitka Magnetic

Observatory clock-driven recorder; (4) Hawaiian Volcano Observatory type clock-driven recorder; (5) Tucson Observatory electric motor-driven recorder, east-west component, governed by a vibrating reed; (6) Tucson Observatory electric motor-driven recorder, north-south component, governed by a vibrating reed; and (7) Georgetown University Observatory spring motor-driven recorder equipped with ball-governor.

The positions of time-marks made at intervals of two seconds on the grams were measured with a comparator reading hundredths of a millimeter. One set of 30 measurements was repeated on each gram, the settings being made on different parts of the same time-marks, as a check on the accuracy of the reading. The time of a mark within a minute-interval was calculated by linear interpolation between the ends of the minute, and this time was compared with the time at which the mark was made by an accurate chronometer.

For example, the positions of the ends of one of the minute-intervals measured were 0.89 mm and 30.38 mm. If we calculate the position where we ought to have found the mark made at, say, 18-seconds phase between these two, assuming uniform rotation, we find it to be 9.74 mm. But this mark was actually measured at 9.64 mm, giving an error of 0.10 mm. We average a number of errors calculated in this way for one recorder. The result is then converted to seconds by taking account of the paper speed.

If we have a gram on which appear marks made at consecutive 2-second intervals over a period of m minutes, the number of possible comparisons of this type is 30 (30m - 29), which is impracticably large if m > 1. We select a random sample from these 30 (30m - 29) errors, but limit the randomness in one respect; we use just as many errors at each phase in the minute-interval as at each other phase and thus avoid errors due to the fact that the discrepancy between observed and calculated times should be larger near the middle of the minute-interval than near the ends.

Standard errors (that is, root-mean-square averages of the errors measured) were determined from the measurements described above on the various drums tested. The checks made on the accuracy of the reading permitted a determination of the standard error of reading. The small error introduced in calculating was also determined approximately. The error measured directly was corrected for these two errors by least-square methods, so as to leave a residual error, σ_{drum}, due to the irregularities of the drum alone.

The results obtained are given in Table 1, which shows for each recorder the following data: n = number of selections made from the 30 (30m - 29) errors in calculating the average error; σ_{drum} = standard error of the drum in seconds; and σ_{min} = standard minute-to-minute change of length of the minute-interval in millimeters for comparison with σ_{drum}, as explained later.

Table 1

Recorder	Type of drive-control	Paper-speed	n	σ_{drum}	σ_{min}
		mm/min		s	mm
Honolulu, N-S	Clock	8	60	0.76	0.26
Honolulu, E-W	Clock	8	60	0.54	0.14
Sitka	Clock	16	120	0.34	0.25
Hawaiian Volcano	Clock	30	90	0.25	0.31
Tucson, E-W	Vibrating reed	30	60	0.19	0.47
Tucson, N-S	Vibrating reed	30	60	0.16	0.34
Georgetown	Ball-governor	30	120	0.05	0.09

In obtaining these data the time-marks were flashed on the drums at 2-second intervals for all the drums except the Honolulu, where 4-second intervals were used. The number, n, of comparisons made was taken large enough so that the standard error of σ_{drum} was less than 10 per cent of σ_{drum} itself in every case.

We are not interested so much in the smaller errors as in the frequency with which large errors will occur. Knowing the standard error, we can obtain this frequency from standard-probability tables, provided the distribution is sufficiently

nearly normal. Now the nature of the data is such that it is reasonable to expect the distribution of errors to be fairly nearly normal, at least for errors not large in comparison to the standard error. To confirm this expectation the errors observed for the Sitka recorder were used to calculate the kurtosis, which was found to be slightly negative. This means that the departure of the distribution from normality, if significant at all, is probably in the direction which would tend a fortiori to justify the conclusions we draw here from the probability table on the assumption that the distribution is normal. In Table 2, which is taken from standard-probability tables, we show the average number of measurements required to contain one measurement at least as high as x, for a normal distribution with standard error σ.

Table 2

x/σ	No. of measurements required
0.67	2
1.0	3
1.5	7
2.0	22
2.5	81

(The first argument in Table 2, 0.67, is the probable error, the value for which larger and smaller errors occur with equal frequency.)

We can at this point assume a fairly suitable criterion for the satisfactoriness of performance of a recorder. Suppose we assume that an error as large as one second is small enough in telesseismic work, and that a drum for which a larger error than this occurs only once in 20 times will be considered satisfactory. From the Table we see that the value of x/σ for which a larger error occurs only once in 20 times is about 2; here we are taking x = 1 second, and so σ will be one-half second. That is, for telesseismic work the value of σ_{drum} for which smaller errors are satisfactory and larger ones are not is in the neighborhood of one-half second. (This criterion is, of course, rather crude. The reader may make his own assumptions corresponding to those of the last paragraph, and derive a criterion more satisfactory to himself. In this connection Miss I. Lehmann has pointed out (Earthquake Notes, v. 4, No. 3, 1932) that the error should be smaller for an isolated station than it need be for a station which forms one of a group.)

Returning to the errors tabulated for the various recorders, we see that they are all satisfactory (if we use the above criterion) except for the old recorder at Honolulu.

We have mentioned above that the error should vary with the phase in the minute-interval, being largest near the middle. In order to study this variation we obtained for each drum the value $\eta_{phase}/\sigma_{drum}$, where η_{phase} is the mean absolute error as a function of the phase, while σ_{drum} is the standard error over all phases. These values of $\eta_{phase}/\sigma_{drum}$ were averaged for all the drums tested, and then multiplied by 1.25331 to obtain $\sigma'_{phase}/\sigma_{drum}$. (1.25331 is the ratio σ/η for a normal distribution. We denote by σ'_{phase} the values calculated by this method, which is more convenient than a calculation of σ_{phase} itself would be.)

These values of $\sigma'_{phase}/\sigma_{drum}$ are plotted as a function of the phase in Figure 1, and a smooth curve drawn among the points. We see that the error increases as we approach the middle of the minute, as we expected. If we know the standard error of a recorder and the position in the minute-interval of an impulsive movement on the gram, we can find the standard error to apply to the time of this impulse by multiplying the standard error of the recorder by a value read from this curve as a function of the phase. Table 3 shows readings from the smooth curve.

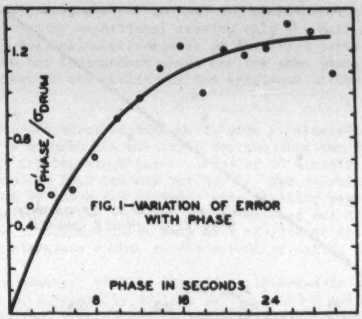


Table 3

Phase	$\sigma'_{phase}/\sigma_{drum}$	Phase	$\sigma'_{phase}/\sigma_{drum}$
s s		s s	
0 or 60	0	16 or 44	1.11
1 or 59	0.12	17 or 43	1.13
2 or 58	0.24	18 or 42	1.15
3 or 57	0.36	19 or 41	1.17
4 or 56	0.46	20 or 40	1.19
5 or 55	0.55	21 or 39	1.20
6 or 54	0.64	22 or 38	1.21
7 or 53	0.71	23 or 37	1.22
8 or 52	0.78	24 or 36	1.23
9 or 51	0.84	25 or 35	1.23
10 or 50	0.89	26 or 34	1.24
11 or 49	0.94	27 or 33	1.24
12 or 48	0.98	28 or 32	1.25
13 or 47	1.01	29 or 31	1.25
14 or 46	1.05	30	1.25
15 or 45	1.08		

It will be seen that the point at phase 2 seconds is not very closely on the curve, which we have drawn through the origin, and we may not, therefore, use this Table with so much confidence for phases near the ends of the minute (say within 4 seconds), as elsewhere.

In the paper referred to above, Macelwane has suggested several measures, based on the lengths of the minute-intervals, of the errors of recording-drums. Of course, this type of measure is subject to errors which the present more elaborate analysis precludes; thus if the only error in a drum is a periodic motion which recurs every minute, the lengths of the minute-intervals will all be the same, but the error will not be zero. Nevertheless, on account of its simplicity, a measure of this type would be well worth having if it could be expected to give us even a rough estimate of the error of the drum. An empirical relation was sought on the basis of measurements made on the seven drums listed above.

The root-mean-square minute-to-minute change of length of the minute-interval, σ_{min}, was calculated, corrections being made for error introduced in reading and calculating as before. These values in millimeters are shown in Table 1. The values of σ_{drum}, also shown in Table 1, were converted to millimeters and plotted against the values of σ_{min}. The choice of millimeters instead of seconds as the unit used in making this correlation is largely a question of weighting; it is thought that the method

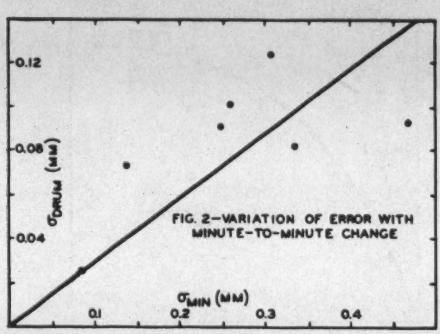


FIG. 2—VARIATION OF ERROR WITH MINUTE-TO-MINUTE CHANGE

used will give slightly better results for the recorders dealt with here. (When the values of σ_{drum} were converted to millimeters, the results for the four clock-driven recorders were found to be much more nearly equal than the same values in seconds, but this agreement is fortuitous, for with a given clock the value of σ_{drum} in millimeters would vary as the diameter of the drum.) These points are shown in Figure 2, where the regression line through the origin is drawn. Its equation is

$$\sigma_{drum} \doteq 0.29\ \sigma_{min} \qquad (1)$$

The standard error of the regression-coefficient, 0.29, obtained here is about 0.08, which is small enough to assure us that (1) should be a useful formula. To obtain an approximate value for the error of a recorder, we find the root-mean-square average of the changes in length of successive minute-intervals, in millimeters, multiply by 0.29, and then convert to seconds by taking account of the paper-speed. This gives us the standard error, σ_{drum}, in seconds.

It is interesting to compare the accuracy of the various clocks used in driving seismograph-recorders. The smallest standard error shown in Table 1 for a clock-driven drum is 0.25 second. If we apply the above method of calculation to the results given in Tables 1 and 2 of Macelwane's paper referred to above, we find two clock-driven recorders, namely, the Quervain and the Galitzin-Wilip, for which the standard error appears to be considerably less than 0.25 second. So long as we are not concerned with accuracy better than one second, a standard error as high even as one-half second is, as we have seen, not too large. But if we are interested in the study of local quakes, or for any reason wish to achieve an accuracy approaching one-tenth of a second, we must considerably increase the accuracy of our driving-mechanism. A clock-drive has one advantage over a synchronous motor; inasmuch as its motion is periodic, its error once determined can be fairly well relied upon, while the source of synchronous power is subject to the possibility of large unexpected variations. But the increasing demands for precise timing in seismology are such that it is questionable how long the less accurate clocks will continue to be satisfactory.

We have confined attention here to the mean error of a recorder, and not attempted to determine the maximum error possible. It would evidently be a laborious task to take account of enough data to enable one to say with any confidence what the maximum error that can occur may be. Perhaps the best approach to this problem would be made by studying the sources of error; to get the maximum error one would then consider the case in which these sources are all additive in one direction. Two of the most serious sources of error are likely to be irregular motion due to play and unbalance of the drum, and systematic irregularities due to the gears or individual teeth of the gears of the driving mechanism. This second type of error lends itself readily to study. To determine what error is due to a gear of some period--say one-half minute--we superpose on each other successive sets of values of the rate of rotation of

the drum in periods of one-half minute, and add the corresponding terms. This process smooths out the irregular variations, leaving only the half-minute wave, if it is present. By performing this calculation twice on different parts of the data for the same recorder, we obtain two independent waves for the same gear; comparison of these furnishes us a simple test of the reality of the existence of the wave under investigation.

Measurements of the positions of time-marks made at intervals of 2 seconds over a period of 29 consecutive minutes are available for the Hawaiian Volcano type recorder. One of the gears in the driving-clock has a period of 30 seconds, and one set of teeth in its gears has a period of 28.2 seconds per tooth. The calculation described above was carried out for each of these two periods, with striking results. In fact the correlation between the two curves for each period studied was higher than one would expect from random sets of numbers in as many as a million trials. (It is hoped that one of us will publish elsewhere a note on the method of making this calculation.)

It is fair to ask, however, whether the effect observed in studying the 30-second wave is not due to the mere proximity of this period to 28.2 seconds, for which a real wave exists, or vice versa. Accordingly, a similar study was made to determine whether a 29-second wave was present. The correlation-coefficient in this case, in contrast to the previous cases, was insignificant, being less than its standard error. The effects due to these two sources of error are thus well separated.

An interesting difference between these two effects is brought out in the analysis: The wave found for the 28.2-second period was much smoother than the 30-second wave. This is what we should expect if we attribute the 28.2-second effect to a departure of the shape of the teeth of the gears from the shape which would transmit the motion uniformly, but attribute the 30-second effect to irregularities encountered as we go around the 30-second gear. The regular wave is the source of greater error, because when departures of the same sign persist in succession, they accumulate to give larger errors than can occur if positive and negative departures from the average rate of rotation succeed each other more nearly at random. In fact, it is probable that the replacement of the two gears having 28.2-second teeth with gears cut for uniform transmission of the motion would suffice to eliminate most of the error due to this clock. The arrangement of the gears in the cases of the other clock-driven recorders listed in Table 1 is such that it is reasonable to expect larger errors from these clocks than from the clock driving the Hawaiian Volcano recorder, and these errors are actually found to be larger, as we see in the Table.

Some progress has been made at the United States Coast and Geodetic Survey with the elimination of errors in magnetograph recorder-clocks by replacing the gears, but this work is not yet complete.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE TRANSMISSION OF SEISMIC WAVES

Frank Neuhann

In studying the instrumental results of the Santiago, Cuba, earthquake of February 3, 1932, the author was particularly impressed by the almost linear character of portions of the travel-time curve for the P-wave, and for other wave-groups in the interval between P and S. Two important conclusions have been suggested by this study, both of which pertain to fundamental conceptions of Earth-structure and to the transmission of seismic waves.

If we modify the usual smooth type of travel-time curve by flattening out certain sections, we introduce sharp bending points in the curve and such points must be taken to indicate the presence of additional shells. The rather limited data for the Santiago shock indicate that one of these sharp changes in slope corresponds to a discontinuity about 350 km deep. A discontinuity near this level has already been suggested by Mohorovičić and others, but seismologists in general have apparently been reluctant to accept it. The data also indicate that another discontinuity may be

present near the 800-km level, but the data on which this is based are indefinite. The first generally accepted major discontinuity near the 1,200-km level is evident in the Santiago curve by a bend near 5,500 km.

The flattening of sections of the curve also indicates more constant velocities within the shells and sharper discontinuities, and it is of fundamental importance to determine to just what degree we might carry this idea. We now accept depth-velocity curves which are of smooth character from beneath the continental layers down to the so-called liquid core. The changes are gradual and not a series of abrupt changes which would imply sharply defined shells. The extreme hypothesis would postulate a series of shells in which the velocity-characteristics were uniform throughout each shell. It is believed that the Santiago data present evidence which indicates either an approach to this condition or a condition which may be considered an important modification of our present conceptions of Earth-structure.

There is no doubt that the early investigators seriously considered the hypothesis of an Earth composed of sharply defined shells, but only those familiar with the uncertainties of seismic data can appreciate the difficulty of obtaining in their day data of sufficient accuracy and quantity to prove or disprove such an hypothesis. The only rational thing they could do was to draw a smooth unbroken curve to represent the surface travel-time of the P-wave. This practice has apparently been followed down to the present time without serious question, even though the available data are far superior to the data available in the earlier days of seismological research. This is a natural result of the greater distribution of high-grade instruments, additional stations, and not least, efficient time-service made available through the development of radio communication. We in North America are especially gratified that a seismological service is being developed, which even now may be said to constitute a new zone of intensive research comparable with those of Europe and Japan.

The uncertainties involved become more pronounced when we attempt to explain activities between P and S on the basis of an unbroken P-curve and the explanation of interior structure which it indicates. Many groups can be selected for which there is no apparent explanation.

Another source of uncertainty lies in the practical absence of observed "angle of emergence" data at the shorter epicentral distances. A tabulation of reliable data would clear up all the uncertainties pertaining to discontinuities above the 1,200-km level. The nature of trajectories below 1,200 km is such that it is difficult to distinguish between a continuous curve and one consisting of a series of straight lines, each of which corresponds to the trajectory through a specific shell. The uncertainties discussed apply more to the zone above 1,200 km, although theoretically they apply also to the deeper layers.

There are thus three reasons why one may question the continuous nature of travel-time curves: (1) More than one investigator has pointed out that certain elements of the P-curve are almost linear in character although no one has in recent years (as far as the author knows) suggested that they might be discontinuous; (2) the explanation of observed activities between P and S does not apparently favor one theory any more than another, a condition which obviously offers a promising line of attack on existing uncertainties; and (3) observational data on the angle of emergence is hopelessly inadequate to define the paths of seismic rays which do not penetrate beneath the 1,200-km discontinuity.

To the student of Earth-structure these ideas have the following significance: (1) The various shells may be much more sharply defined and more constant in physical characteristics than now generally conceded by seismologists; (2) the sphere outside the accepted 1,200-km discontinuity may consist of 2 and probably 3 shells (excluding surface-layers) of sharply different physical nature.

Discussion of data

The illustrations are intended to show evidence of the uncertainties just discussed. Before referring to the data of the Santiago shock, however, attention is called to the theoretical types of travel-time curves which would be obtained for various types of shells and discontinuities. L. B. Slichter has covered this subject

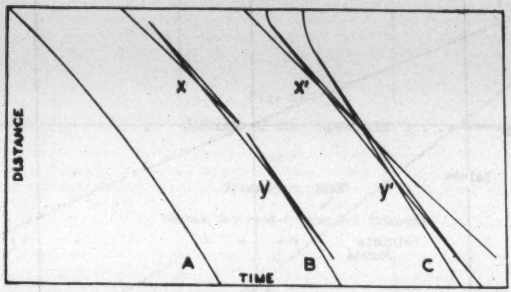


Fig. 1--Types of travel-time curves: (A) Gradual increase of velocity with depth, no sharp change in slope; (B) two discontinuities indicating very rapid, but not immediate increases in velocities at the discontinuities; (C) two discontinuities indicating practically constant velocities within the shells and sharply defined discontinuities

for horizontal layers in an excellent manner in a recent article entitled "The theory of the interpretation of seismic travel-time curves in horizontal structures" (Physics, v. 3, 273-295, December, 1932). As the important part of this discussion refers to the shorter epicentral distances, there will be no great deviations from the general types of curves used in his illustrations.

The first illustration in this paper is self-explanatory. The problem of the seismologist is to determine which type of travel-time curve fits his instrumental data best. This is difficult for many reasons which will not be discussed in detail. It is highly important, however, to note in the three illustrations that lines drawn through points representing first onsets will be practically identical in all cases. How then can we expect to determine the nature of discontinuities from the first onsets alone? The differences may be less than the combined errors of observation and regional fluctuations in travel-time. It seems that the practice of arbitrarily ignoring activities which follow immediately after the onset, automatically rejects available evidence of fundamental importance.

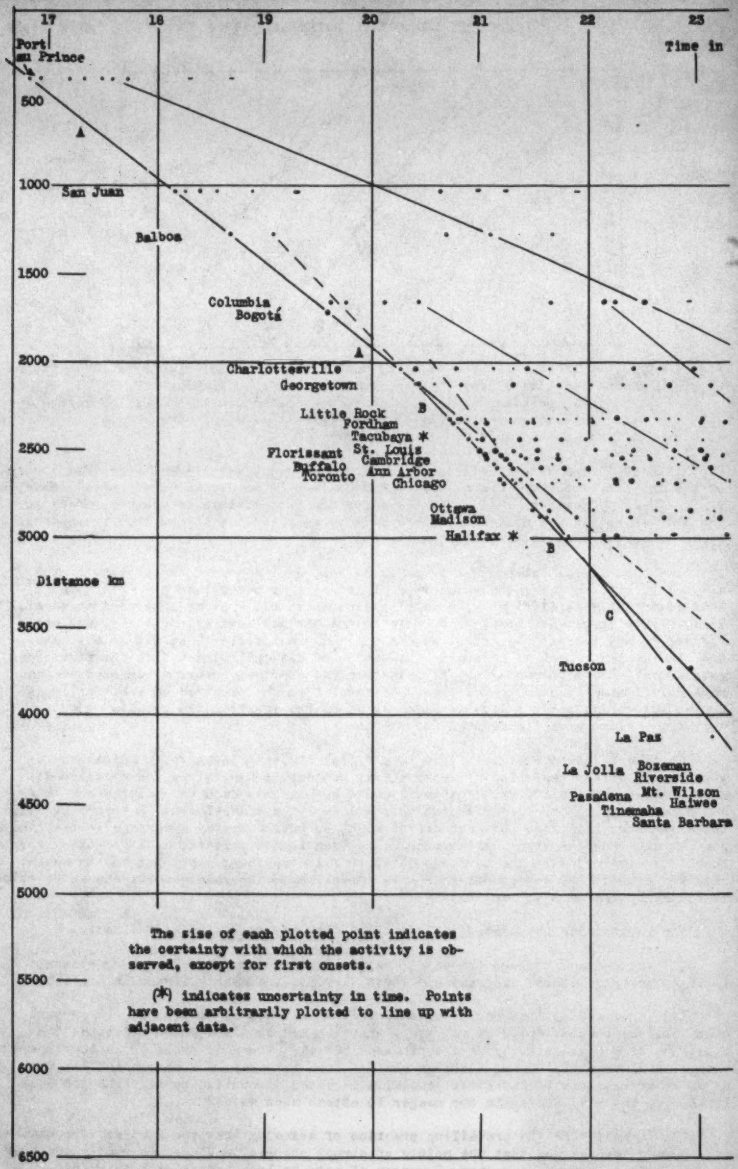
It is not intended at this time to use the data as a basis for qualitative results to construct new velocity-depth curves or compute new values for possible discontinuities above 1,200 km. Much work could be put into such an analysis and this would be a logical procedure; but at this writing, the time-element is important and the writer has felt that the next effort might be put to better advantage in securing similar data for the other earthquakes. The idea is not that the data for other shocks should be combined with the Santiago data, to fill important gaps, but to see whether observed activities, subsequent to P-wave onsets, have the same general characteristics indicated by the Santiago data.

The outstanding features of the Santiago data may be listed as follows:

(1) Lines drawn through the onsets may be divided into four groups or elements (within the range of the diagram) and these elements are nearly linear in character.

(2) If we assume that the P-curve (for first onsets) is continuous, it appears quite obvious that at 2,100 km we have a sharp change in slope which indicates the existence of a discontinuity at a depth near 400 km. There is probably another sharp change in slope at 3,100 km, although the evidence is weak. The change indicated at 5,500 km corresponds to the first generally accepted discontinuity near the 1,200-km level, but the data are again too meager to attach much weight to.

(3) If we ignore the prevailing practice of assuming that the P-curve is continuous, we may then assume that the points of abrupt changes in slope are really the overlapping points of four elementary P-curves of more or less independent character.


17
18
19
20
21
22
23
Time in
Port au Prince
500
1000
San Juan
Balboa
1500
Columbia
Bogotá
2000
Charlottesville
Georgetown
Little Rock
Fordham
Tacubaya *
2500
Florissant
St. Louis
Cambridge
Buffalo
Ann Arbor
Toronto
Chicago
Ottawa
Madison
3000
Halifax *
Distance km
3500
Tucson
4000
La Paz
La Jolla
Bozeman
Riverside
4500
Pasadena
Mt. Wilson
Tinemaha
Haiwee
Santa Barbara
5000
5500
6000
6500
A
B
C
The size of each plotted point indicates the certainty with which the activity is observed, except for first onsets.
(*) indicates uncertainty in time. Points have been arbitrarily plotted to line up with adjacent data.

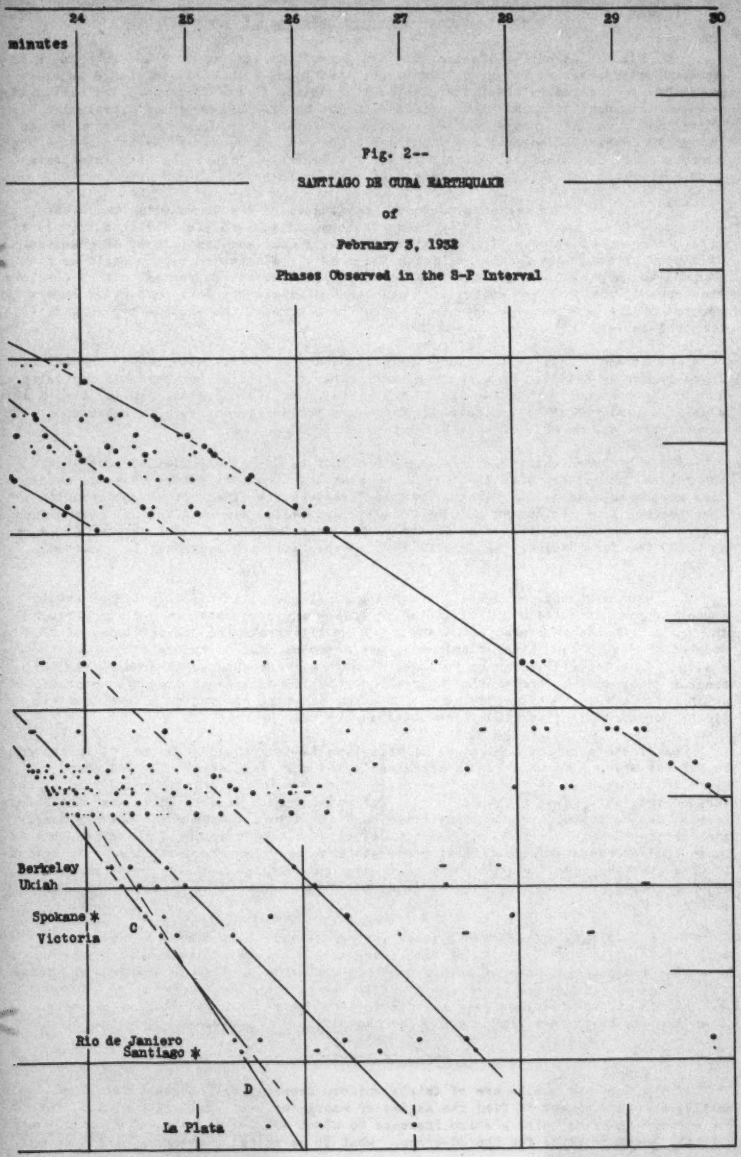


Fig. 2--

SANTIAGO DE CUBA EARTHQUAKE

of

February 3, 1932

Phases Observed in the S-P Interval

(4) Element AA may be considered as quite well defined up to 2,100 km. There is abundant evidence that it may extend beyond that point with a slight change in slope where it is preceded by the faster travel-time onsets of the BB-group. The similarity between this condition and that indicated on the theoretical types of travel-time curves (at x and x^1) should be given particular attention, for if the P-curve can be proved to consist of several overlapping elements we must abandon the notion of a continuous curve for all first onsets. This, incidentally, infers that the interpretation PR_1, given to activities in this zone, may be in error.

(5) Element BB is marked by a sharp speeding up of the travel-time to Toronto, Chicago, Ottawa, and Madison. Their locations would seem to indicate that this is a regional phenomenon, possibly connected with the great Canadian outcrop of granites. It may be of even more fundamental significance. If element BB is prolonged we find perhaps the best coincidence with the more complex theoretical curves. It is possible that some of the observed activities registered at distances less than 2,000 km are records of the same wave-group. Note again the nature of the various types of theoretical curves.

(6) Element CC is well defined in sections and of practically linear character. There is strong evidence of a backward extension of this line but there is confusion due to the presence of the AA- and BB-activities. In 1929 Repetti (Manila) traced a similar activity back to the origin. There are not sufficient data to substantiate nor disprove a forward (or downward) extension of CC.

(7) A backward extension of element D cannot be definitely claimed, but if the theoretical curves are examined it will be seen that the outstanding observed activities may be related to it. At the greater distances the effect of sharp discontinuities becomes less pronounced and the seismic rays become almost identical with curved rays. This should be considered in evaluating correlations at these greater distances. At 5,000 km, for instance, we find PR in its expected place according to accepted theory.

(8) When stations are closely grouped and all the activities plotted we should expect to find it quite a simple matter to follow any pronounced wave-train through the group. The data between 2,000 and 3,000 km illustrate the possibilities of this mode of attack to determine seismic-wave trajectories and the nature of the upper shells. Some activities can be followed through with reasonable assurance. As the diagram gives surface travel-time and velocity it is possible to draw trajectories which will satisfy this limited amount of data, assuming discontinuities at certain depths, or assuming discontinuities obtained by other means.

One of the clearest activities of this type is near the S-group and is indicated by a ruled line. The velocity is practically the same as element AA. The phase might be interpreted as a normal P-wave (80 km/sec) which is partly transformed at the surface into an S-wave, which is in turn reflected from a discontinuity near the 350-km level. The reflected wave is transformed back again to a P-wave which travels nearly parallel to the Earth's surface. Such conclusion must be considered tentative, but if these conjectures stand the test of other studies, they become outstandingly important. In this case the result argues for a sharp discontinuity at the level mentioned. The other activity, indicated by a ruled line, may be interpreted as a continuation of Jeffreys' S_g.

There is plenty of room for further conjecture but the writer's purpose is to call attention to possibilities of future research along this line rather than exhaust the innumerable lines of conjecture which could be applied to the Santiago data.

(9) No attempt has been made to analyze the S-wave and a smooth line has been drawn through the S-wave group merely for identification purposes.

Angle of emergence

If the interior shells are of fairly uniform density, or "constant-velocity" shells, we would expect to find the angles of emergence very small (10° or 15°) for the element AA-waves, with a sharp increase to about 45° for the element BB-waves, and slightly greater values for the CC-group. What do we actually observe? Galitzin was

the only investigator, as far as the writer knows, to attempt a tabulation of these important data. He tabulates nothing below 2,500-km epicentral distance. His first significant figures are as follows, the computed values being from smooth travel-time curves:

Distance (km)	2,500	3,000	4,000	5,000	6,000	7,000	8,000
Observed	48°	44°	42°	44°	48°	54°	62°
Computed	42°	47°	54°	60°	62°	63°	64°

These observed data do not confirm the idea of continuous travel-time curves. The nearly uniform observed value between 2,500 km and 6,000 km argues strongly for constant-velocity shells and sharp discontinuities. It is the writer's opinion that the greatest need in instrumental seismological research today is observational data on angles of emergence at the shorter epicentral distances. It is in practice a very difficult problem and seems to call for a special type of equipment.

Data pertaining to the Santiago earthquake

The Coast and Geodetic Survey is indebted to those in charge of various seismological institutions for the loan of original seismograms or copies. Without this generous cooperation the present study could not have been made.

The coordinates of the epicenter are based principally on the data from stations at epicentral distances less than 2,000 km, namely, Port au Prince, San Juan, Balboa, and Bogotá. The first onset at Columbia was uncertain. Distances are all computed. The adopted time of origin is uncertain because of lack of a sufficient number of stations in the region of the West Indies.

Date of Santiago de Cuba earthquake, February 3, 1932; adopted time of origin, $6^h\ 16^m\ 00^s$, G. C. T.; coordinates of epicenter, 19° 50' north and 75° 50' west.

Discontinuity at 350 kilometers

The sharp change in slope of the travel-time curve near 2,000 km was noted by Mohorovičić who postulated a discontinuity at 400 km on the basis of a continuous travel-time curve, utilizing the theory of integral equations to determine depth. Byerly called attention to a similar bend in his curve for the Montana earthquake. It is quite by chance that we get a nearly equal depth of discontinuity if we calculate it on the theory that this outer shell is practically a "constant-velocity" shell with a sharp increase in velocity below the discontinuity. In other words, the maximum depth of the curved ray at an epicentral distance of 2,100 km is near the depth of a ray which travels along straight paths in the shells above and below the discontinuity. The velocity in the upper shell is indicated by the slope of element AA; and in the lower shell by the slope of element BB. In estimating the depth on the "straight-ray" hypothesis it was arbitrarily assumed that the focus was at the base of two continental layers totaling 40 km in thickness. A value of 370 km was obtained. Any revision of the value should be downward because it would seem from the presence of an Sg-wave that the focus was relatively shallow. Three hundred fifty kilometers or less might be considered a better working value.

U. S. Coast and Geodetic Survey,
Washington, D. C.

CONSTANTS OF THE WENNER SEISMOGRAPH

A. Blake

(Abstract)

The method of McComb and Robison, with some minor improvements, was used by McComb and the author to determine the constants of the new instruments for Sitka. When these are known, and operation constants--damping, period, and optical lever--have been chosen, the magnification curve can be calculated by the method given by Wenner.

The magnification is zero for infinitely long periods, and again for infinitely quick vibrations, differing in this latter respect from the ordinary seismograph, whose harmonic magnification is one for infinitely rapid motion. For finite periods the magnification-curve rises to a maximum and then falls off. It is possible to have an instrument of this type in which this curve has two maxima, but in the instruments actually used it has only one.

The damping and natural period are not precisely defined for this instrument, but are taken by Wenner as those of a fictitious instrument of the lever-recording type obtained by considering the performance of the galvanometer to be the ideal performance in which no current is consumed. This assumption is tested by studying the roots of the characteristic equation for the motion of the system, and found to be well justified for suitable intermediate periods. This treatment leads to an improvement in the method of making the damping-tests.

U. S. Coast and Geodetic Survey,
Washington, D. C.

PROPOSED NEW EARTHQUAKE-CODE

Watson Davis

The cooperation of the United States Coast and Geodetic Survey, the Jesuit Seismological Association, and Science Service with seismological stations throughout the world, particularly in the United States and Canada, has now continued for some eight years. During that time the same code has been used. It has now become advisable to make a revision of that code because more information can be transmitted than was contemplated when the earthquake reporting-and-location system was first inaugurated, and also because a change in telegraphic practice will allow the reduction of telegraphic tolls, borne by Science Service, to about one-half of the present cost.

When the earthquake-code was first introduced, we adopted the substitution code used by astronomers in which two letters, one of them a vowel, substituted for each number in coding the data. This made each group of five figures take the form of a pronounceable ten-letter word. Since 1925 the telegraphic regulations have changed so that now any group of five letters is counted as a word and therefore the cost of sending five figures by wire when coded into ten letters is two words instead of one. It is now proposed to substitute a single letter for each figure, thus making it possible to send by telegraph five figures at the cost of one word.

Suggestions and comments from all those concerned were requested, and as a result of the discussion a committee was appointed which took the matter under consideration. The result was a revision of the code which is being issued by Science Service on behalf of the three cooperating organizations to the seismological stations with the request that the new code be used as soon as convenient. The following participated in the formulation of the new code: Beno Gutenberg, Seismological Laboratory, Pasadena, California; Joseph S. Joliat, S.J., Saint Louis University; James B. Macelwane, S.J., Saint Louis University; Frank Neumann, U. S. Coast and Geodetic Survey; R. R. Bodle, U. S. Coast and Geodetic Survey.

Science Service,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

Fourteenth Annual Meeting

SECTION OF HYDROLOGY

Washington, D. C., April 27 and 28, 1933

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ON THE HYDROLOGY OF SNOW

J. E. Church, Chairman

The ideals formulated in the first annual report (1931-32) have already begun to move toward realization. Cooperation, standardization of methods, and publicity of results have been notably advanced during the year.

Conferences

Conferences with the Chairman of the Section of Hydrology--On October 31, 1932, Chairman Meinzer met the Nevada snow interests in conference at the Nevada Agricultural Experiment Station. Other members of the Committee on the Hydrology of Snow were met by him in Utah and California. This custom should be continued and should also be adopted where financially possible by Committee chairmen.

Western Interstate Snow-Survey Conference--Through the enthusiasm of Professor George D. Clyde, eastern Great Basin representative on the Committee, and quite contrary to the tendency set by the depression, a personal conference on research problems expanded into an Interstate Conference on snow-surveying, embracing all of the central and northern states from the Great Divide westward to the coast. The response was eager and the interests unexpectedly wide. Personal representatives from Utah, California, and Nevada met at the Nevada Agricultural Experiment Station, the pioneer in western snow-surveying, on February 18, 1933, as guests of the University of Nevada. There was a registration of 30 from Nevada, 8 from California, and 2 from Utah. Representatives from southern California were blocked from attending by snow.

As reported by the Conference secretary, Harlowe M. Stafford, Snow Supervisor of California, "It was felt that the Conference was highly successful and of great value not only in permitting a discussion and clarification of the many problems connected with snow-survey work both in forecasting stream-flow and research, but in fostering a better realization upon the part of the general public of the importance and value of this activity in the western states.

"At the conclusion it was voted that the Conference should be made an annual meeting to be designated as the Western Interstate Snow-Survey Conference and that future conference arrangements and publications of proceedings should be in the hands of an Executive Committee of five, elected each year. It was desired that the representation on the Executive Committee should be as wide as possible and the following were elected for this year: Harlowe M. Stafford, Chairman, Snow Supervisor, Division of Water Resources, California State Department of Public Works; J. E. Church, Meteorologist, Nevada Agricultural Experiment Station; George D. Clyde, Professor of Irrigation and Drainage Engineering, Utah Agricultural College, Utah; W. C. Lowdermilk, Senior Silviculturist, U. S. Forest Experiment Station, Berkeley; and V. H. Greisser, Chief Engineer, Washington Water Power Company."

The records of the meeting have been prepared for mimeograph publication by Secretary Stafford and Emily Richards, Nevada, Assistant. The detailed program as carried out is given in order to set forth graphically the many problems seeking solution and the many organizations involved.

The program of the Conference was as follows:

Greeting. S. B. Doten, Director, Nevada Agricultural Experiment Station.
The biography of snow-surveying. J. E. Church.
Organization. G. D. Clyde, Chairman.
(1) General problems, H. M. Stafford, Leader:
Progress and conduct of California cooperative snow-surveys. H. M. Stafford.
History and conduct of snow-surveys in Utah. G. D. Clyde.
Financing. A. V. Tallman, Supervising Water Commissioner for Humboldt River, Nevada.
Cooperation. E. H. Bowie, Meteorologist, U. S. Weather Bureau, San Francisco; Alexander McQueen, Forest Supervisor, U. S. Forest Service, Elko, Nevada; C. L. Forsling, Director, Intermountain Forest and Range Experiment Station, Ogden, Utah.

(1) General problems--continued:

Early forecasts in irrigation terms. Edward C. Reed, County Extension Agent, Reno, Nevada; Prof. H. P. Boardman, Chairman, Nevada Cooperative Snow-Surveys; Cruz Venstrom, Crop Economist, Nevada Agricultural Experiment Station.

Importance of snow-surveys to State engineer's office. George W. Malone, State Engineer of Nevada.

Equipment--Snow-samplers, shelter-cabins, ski. Spencer Munson, Hydraulic Engineer, California Division of Water Resources; G. D. Clyde; Frederick Herz, Assistant, Nevada Cooperative Snow-Surveys.

Methods of conducting field-work: (a) Snow-surveyors at work (a lantern-slide trip). Spencer Munson. (b) Helpful hints in skiing and driving sampler. Frederick Herz, Nevada.

Publications.

(2) Technical problems:

Normals. H. P. Boardman; George V. Sager, Meteorologist, U. S. Weather Bureau, Reno, Nevada; Spencer Munson. Discussion by C. L. Forsling and F. C. Scobey.

Snow-water ratios. E. H. Bowie; H. I. Snider, U. S. Forest Ranger, Tahoe Forest, Truckee, California; G. V. Sager.

Types of courses.

Zoning. Spencer Munson.

Bridging.

Factors affecting runoff: (a) Precipitation during runoff. Spencer Munson. (b) Temperature. G. D. Clyde; J. E. Church.

Accuracy of forecasts. H. M. Stafford and Spencer Munson; H. P. Boardman.

Irrigation maps. F. C. Scobey, U. S. Bureau of Agricultural Engineering, Berkeley, California.

Relation of forests to snow. Joseph Kittredge, Jr., Professor of Forestry, University of California.

Considerations in measurement of yield of snow-packs in percolation of water. W. C. Lowdermilk, Senior Silviculturist, California Forest Experiment Station, Berkeley, California.

Special problems: (a) How often will Lake Tahoe under present regulation fall below its outlet in the next 50 years? H. P. Boardman. (b) The Humboldt Basin, Nevada, "the last frontier in stream-flow forecasting." Mr. Tallman. (c) Establishing a snow-survey system for the Colorado. J. E. Church. (d) New regulation of the Truckee River. S. R. Marean, Hydrographer, Truckee-Carson Irrigation District, Nevada.

The Greenland Ice-Cap. (A reminiscent lantern-slide talk on snow-surveying in the Arctic. Informal, while awaiting night trains.) J. E. Church.

General conditions

The general conditions of snow-cover, snow-surveying, and research are best represented by the following resume of reports from the members of the Committee, who represent not only the geographical divisions of the country but the various types of activity interested in snow. As will be readily noticeable, the depression has slowed down but has not completely stopped organized snow-surveying despite financial pressure. The spirit of the year is to keep the continuity of measurements of snow-cover and stream-flow unbroken. Research can wait. However, publication of results remains active.

New England (Paul L. Bean)--Rather extensive studies of snow-conditions along the Androscoggin River and in the Androscoggin Valley in general. Doing the best we can without the expenditure of much money. New York (E. S. Cullings)--In the Adirondacks at the end of March there is only about 50 per cent of the normal accumulation of snow on the ground. Colorado River Basin (E. B. Debler)--Hoped-for program in connection with the Colorado River still delayed. Most investigation work dropped on account of depleted finances. Eastern Great Basin (G. D. Clyde)--Cooperation mainly between Utah Agricultural Experiment Station, U. S. Forest Service, and U. S. Weather Bureau. Research supported mainly by Purnell Fund. Because of abundance of early water, chief interest is in the surveying of high-level snow and making forecasts for the late flow that comes from it. Western Great Basin (H. P. Boardman)--By aid of long normals of runoff, short normals both of snow-cover and runoff are being adjusted to long, parallel normals, that is, to normals covering identical long-time periods for both snow-cover and stream. Owing to sharp curtailment of State expenses, cooperative appropriation for snow-surveys has been discontinued for the biennium of 1933-35. A plan is

under way for the continuation of the basic measurements through district and corporation support. No abatement, however, will be experienced in the Humboldt Basin, whose water-users have expanded the snow-survey system at their own expense and authorized the making of the snow-survey and forecast in the present season despite present stringency of funds. California (H. M. Stafford)--Comparison of unpublished forecasts with actual runoff in the Sierra Nevada for 1932 reveals the following accuracy: Out of the total forecasts for 30 separate streams, 12 forecasts were accurate within 5 per cent and 21 within 10 per cent. Of the remaining 9, there were 5 within 15 per cent; 7 within 20 per cent; and all were within 25 per cent. This is a most satisfying record in view of the fact that in all but three basins the basic period of snow-surveys had not exceeded two years. Pacific Northwest, especially Oregon and Cascades (J. H. Ryan)--In Oregon cooperation is maintained jointly by the State and counties. The snow-surveys have been considerably curtailed the present year on account of the general difficulty of finances which has affected the budgets of all the counties as well as the State Engineer's office. Pacific Northwest, especially Upper Columbia (E. H. Collins)--During these times hydrology-work has been considerably curtailed in the hydro-electric power-industry, owing to the fact the combination of above-normal water-supply and below-normal system-load has reduced the economic value of such work. However, the continuity of field-data is being maintained so that no loss of record will be entailed. British America (Mathew Balls)--The results of the snow-surveys carried on during the past five years in the St. Maurice River Valley are being compiled. In order to check the forecasts of river-flow, it has been necessary to analyze the flow-data over a very long period. The capacities of the largest storage-reservoirs are not definitely known and have only been arbitrarily computed. This has given rise to difficulties in arriving at reliable computations of the natural runoff from areas representing 40 per cent of the watershed which are controlled by five storage-reservoirs. A similar difficulty exists in the Humber Basin, in west central Newfoundland, where approximately one-half of the watershed of 3,000 square miles is undeveloped. Alaska--No snow-survey work is reported. Only storage-sites and stream-gaging are being developed at present.

Questionnaire

The two main projects, namely, a Questionnaire regarding present activities in snow-surveying and forecasting stream-flow, and a Bibliography of all publications in the broad field of snow and ice, are being slowly pushed forward. Of large importance for the standardization of methods is an address list including the names of all interested in snow-surveying and stream-flow forecasting. A large number of names has now been gathered and merely awaits classification and publication. Owing to expense, these minor publications must depend upon mimeographing.

College courses in the hydrology of water and snow--A portion of the Questionnaire is now nearing completion. This covers the teaching of the hydrology of water and snow, particularly in the United States and Canada. The following tabular statement made by Joe Peters, a volunteer student assistant in obtaining and compiling the statistics, will serve as a preliminary report pending publication of a detailed chart containing the names of the individual institutions and courses offered by each. Geographical location seems to have had little bearing on the types of courses offered. So far as learned, instruction in the hydrology of snow is merged in the broader subject of hydrology in general. From 183 schools listed by the Society for the Promotion of Engineering Education, 144 replies have now been received.

Courses offered in hydrology and allied subjects in the United States and possessions and in Canada--(1) Meteorology including movements of the atmosphere, the formation, progress, and prediction of storms; climates of different countries; and methods of taking meteorological observations, keeping records, and interpretation of the same--11 colleges. (2) Climatology including the climates of the Earth--4 colleges. (3) Hydrology including (a) laws of the occurrence and distribution of waters on the surface of the Earth--4 colleges; and (b) factors governing supply of ground-water and the flow of streams and their relation to water-power, water-supply, irrigation, drainage, and sanitary work--6 colleges. (4) General hydraulic engineering including precipitation, evaporation, percolation, and stream-flow--37 colleges. (5) Hydraulics including hydrostatics and kinetics; flow through pipes, over weirs, and in open channels--91 colleges. (6) Hydraulic testing including actual tests for determining the discharge of water through pipes, over weirs, etc.--41 colleges. (7) Water-power in-

cluding stream-flow, hydrographs of actual stream-storage and the relationship to power-houses, irrigation, and floods--22 colleges. (8) Hydraulic design including design of structures involved in water-power--11 colleges. (9) Hydro-electric engineering including consideration of rainfall through various stages to the construction of power-houses--20 colleges. (10) Irrigation and drainage including principles of irrigation-engineering and design of reservoirs, dams, flumes, and canals--37 colleges. (11) Water supply including consideration of precipitation and runoff; consumption of municipalities; and examination, purification, and distribution of water-supply--73 colleges. (12) Storm-waters including conservation, utilization, and control of flood-waters--11 colleges. (13) Hydrographic surveying including actual measurements of streams and lake-soundings--6 colleges.

Snow-surveying in Canada and Newfoundland

The answers to the Questionnaire from British America reveal a strong development in snow-surveying since the Meteorological Service of Canada ordered a Mount Rose snow-sampler for use in the Bow River Basin about 1917. They reveal also a desire for standardization and conference. The following resumé of reports on snow-surveying sets forth the basins or organizations involved and the purpose of the work. So far as possible, the arrangement is geographic.

Nova Scotia--Very small amounts of snow during the past ten years. No great benefit from snow lying in drainage-areas, but interested in rainfall and evaporation for forecasting stream-flow. Quebec--(1) Headwaters of St. Mary River (10 years) by U. S. Geological Survey and Dominion Water Power and Hydrometric Bureau. (2) St. Maurice River (5 years) by Shawinigan Power Company, Montreal. (3) Gatineau Power Company, Ottawa. Ontario--(1) Headwaters of Winnipeg River in Western Ontario for regulation of Lake of the Woods and Lac Seul reservoirs. Survey used not for a definite forecast but only as a guide in making preparation for the reception of spring runoff. (2) Dryden Paper Company, Dryden, Ontario (2 years). (3) Nipigon River Basin (contemplated) by Hydro-Electric Power Commission of Ontario. (4) Abitibi River Basin (contemplated) by Abitibi Power and Paper Company. British Columbia--(1) East Kootenay Power Company [surveys, but not quantitative]. (2) West Kootenay Power and Light Company, Trail, B. C. (3) Dominion Water Power and Hydrometric Bureau, Vancouver, B. C. (4) Greater Vancouver Water District, Vancouver, B. C. (5) British Columbia Electric Railway, Vancouver, B. C. [one snow-depth on Capilano Creek]. (6) Pacific Mills, Ltd., Ocean Falls, B. C. [on Queen Charlotte Sound]. Miscellaneous--(1) Canada Northern Power Corporation ["No quantitative snow-surveys"]. (2) Southern Canada Power Company ["No quantitative snow-surveys"]. Newfoundland--Humber Basin, by International Power and Paper Company of Newfoundland, Ltd. One-half of the Basin undeveloped and inaccessible in winter. Owing to lack of normals, quantitative method is used in place of percentage method. No precipitation-records prior to 1925.

Snow-studies in other countries

Snow-surveying is taking various manifestations abroad. In Switzerland it looks toward glacier-study, in Finland toward the evolution of the snow-cover, in Norway toward power. In Russia snow-studies are cast in the widest possible mould and require only continuity. In Australia the State Electricity Commission of Victoria has organized a series of snow-studies as elaborate as those organized in America and seeks close cooperation. The following analysis of the Questionnaire is not complete but will give a picture of the character and possibilities of the field:

Switzerland--Since 1914 snow-surveying employed in study of growth of glaciers. Special Mount Rose snow-sampler used. Forecasts of runoff are made in individual cases, but not in any systematic way. A Swiss Snow Commission was recently organized. Detailed observations made of snowfall, snow-cover, snow-density, snow-movement, avalanches, ice, runoff, evaporation, and condensation. Italian Alps--On Monte Rosa snow-surveys but no forecast, with special reference to glacier-movement and runoff. Czechoslovakia--Maintains a systematically conducted service touching the hydrology of snow. Conditions on the rivers Elbe, Vltava (a tributary of the Elbe), and the Danube are forecasted daily. In winter 684 stations take daily depth of snow and 385 of them ascertain from time to time the water-equivalent. Monthly topographic maps are prepared showing the quantity of water accumulated in the snow. Study of evaporation of snow and ice only in the initial stage. Austria--From 1893 until 1920 special weekly

bulletins were issued on observations of the snow in Austria. Since 1921 the snow-conditions of Austria have been transferred to the yearbooks of the Central Hydrographic Bureau. Germany--Until April 1, 1932, a forecast-service for water-control existed in north Germany but has now been partially abandoned for lack of funds; 277 precipitation stations were employed. Special investigations have been conducted on snow-cover, ice-formation in rivers, condensation, and evaporation. Sweden--At 380 meteorological stations, the depth of the snow-cover is measured at regular intervals to obtain a general knowledge of the duration and the thickness of snow-cover in the country, except the high mountains. The quantity of water stored in the snow-cover was formerly measured at 100 stations, but the number is now only 12. Forecastings of stream-flow based on surveying of the snow-cover have been made only occasionally. Norway--A Mount Rose snow-sampler was ordered some years ago at Stavanger to forecast stream-flow in connection with power. Denmark--Observations about snow and allied phenomena are undertaken only at ordinary meteorological stations. Even the presence of a snow-cover is only irregularly recorded. Finland--Topographic snow-surveys of depth of snow-cover made from 1922 to 1926. Russia--The activities in snow and ice are directed mainly by the Hydro-Meteorological Committee of the U.S.S.R. and can be best outlined under the following heads: (1) Evolution of the snow-cover; (2) snow-conservation and runoff from snow; (3) snow-drifts and protection; (4) forecasting of rising of spring stream-flow; (5) forecasting runoff including floods; (6) ice-formation and permanent freezing; and (7) arctic ice. A request has been made through American engineers regarding snow-survey methods for possible use in irrigation-projects in the Caucasus. British Isles--No local study of snow-problems. Only possible interest would be in connection with water-works and power-companies in the neighborhood of Ben Nevis, Scotland, the highest mountain of the British Isles. However, statistics are kept of snowfall-frequency and number of mornings with snow lying on ground. The Gulf Stream is too close. Spain--No snow-surveys. Snow-studies are conducted in connection with forests. However, power- and irrigation-projects are operating in the Pyrenees, where snow-surveys and forecasts of stream-flow should have considerable importance. Argentina--No special snow-studies at present. However, it was planned when the Bureau of Geophysics and Hydrology was established to organize an ample snow-service in all of the Andean and Patagonian districts. Lack of funds at present prevents progress. However, the plans will be carried out at the earliest possible moment. British India--No accurate snow-surveying is done in India. However, monthly reports of snowfall and snow-covering on some well-known peaks and passes in the western Himalayas are published in the India Meteorological Department annual summaries. However, in northern India the chief irrigation engineers and the Secretariat of Naini Tal and all officers connected with canals fed by snow-fed rivers would welcome a forecast by the end of January each year stating the probable date by which snow-water will be available at the various headworks on snow-fed rivers. The height of the snow-line might be recorded every year, for discharges with reference to snow-line might give some useful information. South Africa--Falls of snow in the Union of South Africa are infrequent and usually confined to a few mountainous regions. New Zealand--No snow-surveys. Rainfall is very much more important than snowfall in practically all of the important streams. Very little precise work in snow-studies being done. No work on large permanent snow-fields. Rugged nature of country and consequent extreme variations in rainfall at high levels make problems of stream-flow and floods very difficult. Studies confined to hydro-electric power-installations and to the control of rivers dangerous to the community. Australia--The State Electricity Commission of Melbourne, Victoria, is carrying on a large investigation of hydro-electric possibilities in the province. One of the main projects (of approximately 85,000-kilowatt capacity) under consideration has a catchment situated at 5,000-6,000 feet above sea-level, where there is a snow-cover of some 5 to 25 feet deep for about six months of the year. A snow-survey system has been organized and samplers of the Mount Rose type are being employed. A meteorological service is under contemplation and attempts will be made to obtain direct measurements of evaporation, etc., from snow- and ice-surfaces and the seasonal variations of ground-water. Close cooperation with the American Committee on the Hydrology of Snow is requested. Arctic--Snow-surveys and evaporation-studies were conducted by the Michigan-Greenland Expedition, 1926-28, in Greenland, in the study of the alimentation of the Inland Ice. Antarctic--Observations were made of snow-structure by Laurence M. Gould of the Byrd Antarctic Expedition, 1928-30.

Bibliography of snow and ice

As expressed in the first annual report, the bibliography of snow and ice is essential both to research and to the distribution of information, and should be made as

broad and detailed as possible to afford complete service.

One of the greatest Committee rewards is the complete recovery of Dr. Barnes, Committee representative of Ice. He is now busily at work on a detailed Bibliography of Ice in which a brief summary of each work listed will be given.

G. D. Clyde has undertaken to list all works on snow appearing in meteorological and agricultural journals, and H. P. Boardman will excerpt those in engineering. The task will be long and necessarily slow. Funds must be obtained for translators particularly of Russian literature. Whether this work can be supported from research funds still remains unsettled.

Research

Research has been conducted by the Nevada Agricultural Experiment Station in the Little Humboldt Basin, Nevada, on the effect of low-level snows on the forecast, and by the Utah Agricultural Experiment Station in developing a light sampler of aluminum alloy at moderate cost for the moderate snows of the Great Basin. Many problems have also been analyzed by the Nevada Station in revising its pioneer monograph on "Snow-surveying with reference to forecasting stream-flow." Investigations are being conducted by Joseph Kittredge, Jr., Professor of the University of California, on the relation of forests to snow, and by W. C. Lowdermilk, Senior Silviculturist of the U. S. Forest Service, in the measurements of the yield of snow-packs in percolation of water.

International organization

The request for close cooperative effort, coming from Newfoundland, Canada, and Australia, and the advantages of closer association with other countries emphasize the desirability of organizing an International Commission on Snow similar to the International Commission on Glaciers. Such a commission would further the study of the hydrology of snow and ice and supplement the fundamental data underlying the study of glaciers.

Current publications

A fundamental need of the Committee is an international catalog of current literature on meteorology and hydrology. In the Questionnaire, works of first importance were reported but the list is by no means complete. The current literature in America for 1932-33 is wide and quite transcends the narrower bounds of hydrology. However, the list is left wide for the interest it may afford. Some of the works listed have been accepted for publication but have not yet appeared. The call for material and articles on snow-surveying remains undiminished despite the depression.

Snow

(1) General--

W. A. Bentley, Conical snow, Science, April 8, 1932.
Gene Day, Hailstones and weather wonderworks, Taylor-Tycos-Rochester Magazine, October 1932.
R. Del. French, Snowfall in Montreal, Canadian J. Research, May 1932.
R. Del. French, Jewels of the storm, Nature, December 1932.
Charles H. Lee, The technical use that engineers make of United States Weather Bureau observations, Mon. Weath. Rev., January 1933.
Charles D. Reed, Snow rollers, Mon. Weath. Rev., December 1932.
Charles D. Reed, Snowflakes are made to order, Pop. Sci., January 1932.
C. F. Talman, Students of weather meet rigors on peaks, N. Y. Times, Sec. 8, p. 5, April 9, 1933.
H. A. Webb, As falls the beautiful, St. Nicholas, January 1933.

(2) Snow-samplers--

George D. Clyde, Utah snow-sampler and scales for measuring water-content of snow, Circular 99, June 1932, Utah Agric. Exper. Sta.

(3) Snow-surveying--

A. R. Boone, Snow thieves in the high Sierras; measuring-power in mid-winter, Travel, January 1933.

Snow--Continued

(3) Snow-surveying--Continued

J. E. Church, The biography of snow-surveying. (A radio talk delivered by R. M. Gehl during the "Western Farm and Home Hour," January 6, 1933, through Station KGO and nine other stations associated with the NBC-KGO network, Pacific Division, National Broadcasting Company.)

George D. Clyde, Forecasting water-supply, Civ. Eng., October 1932.

George D. Clyde, Methods of alleviating water-shortages on irrigation-projects, Agric. Eng., February 1932.

George D. Clyde, Australia to make snow-surveys, Engin. News Record, August 11, 1932.

George D. Clyde, Forecasting snow runoff of Humboldt River, Nevada, Engin. News Record, August 4, 1932.

E. S. Cullings, Snow-survey of Adirondack Region, March 20-26, 1933, Dep. Public Work (N.Y.), Hudson River Regulating District, Black River Regulating District, Hudson Power Corporation.

E. S. Cullings, Hoarfrost and rime, and Mountain snow-surveys, Taylor-Tycos-Rochester Mag., October 1932.

Calvin Frazer, Measuring evaporation, Taylor-Tycos-Rochester Mag., October 1932.

Swift Paine, Snow-surveyor of the Sierras: J. E. Church, Jr., Amer. Forests, April 1, 1932 (reprinted Sci. Amer., January 1933).

Washington Post, Study in snow-value, Washington, D.C., Editorial, March 1933.

Western Construction News and Highways Builder, July 10, 1932, Snowfall and run-off, and Committee on Hydrology of Snow.

(4) Snow-removal--

Don't forget snow-removal, Amer. City, November 1932.

Fighting snow, slush, and sleet, Amer. City, February 1932.

Howard T. Barnes, Removing--or preventing the accumulation of snow on city streets?, Amer. City, March 1930. (Note--Relisted because of its fundamental viewpoint.)

A. C. Blomgren, Maintaining landing-fields in Idaho during the winter by unique method, Highway Mag., October 1932.

Engineering News Record, Hydraulic snow-plow, December 29, 1932.

C. B. Hart, Heavy-duty power-mowers used as snow-plows, Amer. City, April 1932.

G. A. Hastings, Preparedness for snow-removal, Amer. City, December 1932.

F. N. Hollingsworth, Battling Old Man Winter in the Bay State, Highway Mag., March 1933.

E. C. Knowlton, Snow-removal on Utah State highways, Western Construction News and Highways Builder, April 25, 1932.

D. C. Meyers, Snow-removal in Oak Park, Ill., Amer. City, November 1932.

R. W. McColough, Snow-removal in Nova Scotia, Amer. City, September 1932.

James Montagnes, Keeping Canada's winter roads free from snow by modern machinery, Highway Mag., January 1933.

J. W. Vickrey, Snow-removal on the Victory Highway, Western Construction News and Highways Builder, April 10, 1932.

J. Wilson, Handling ice and snow on city streets, Duluth, Minnesota, Amer. City, December 1932.

American City, January 1932, Tractors build roads in summer and fight snow in winter.

(5) Snowslides--

Popular Science, August 1932, New study in Alps seeks way to end menace of snowslides.

(6) Chemical properties--

S. Francis Williams, Analysis of rain-water and snow at Mt. Vernon, Iowa, Chem. News, v. 145, 40 (1932).

Ice

T. Cunliffe Barnes, The physiological effect of tryhydrol (ice-molecules) in water, Proc. Nation. Acad. Sci., v. 18, 136-137 (1932). [Changes in the growth of water-plants due to using water which has been produced from melting ice as contrasted with water which has not been frozen.]

Arctic

W. H. Hobbs, Greenland, the advances of a decade (1921-1931), in Papers of the Mich. Acad. Sci., Arts, Letters, v. 18, 1933.

Prepared but not yet published

California Division of Water Resources, California, Cooperative snow-surveys, Comparison of April 1st forecasts and actual water-supply, 1932, and Accuracy of forecasts compared to length of period of snow-surveys: South Yuba River at Lang's Crossing.

J. E. Church, Forecasting stream-flow: Report of progress in the Humboldt Basin for the water season 1931-32, Humboldt River Distribution, 1933.

Arthur L. Smith and H. P. Boardman, Snow-surveying with reference to forecasting stream-flow (monograph, approximately 400 pages), Nev. Agri. Exper. Sta.

Snow-surveying: Its principles and problems, J. Agri. Res.

Snow-surveying: Its principles and opportunities, Geog. Rev.

Transactions of the Western Interstate Conference on Snow-Surveying, 1932, Nev. Agri. Exp. Sta.

Appendix

Appended to the present report are the following papers to be placed on file with the Secretary of the Section:

(1) The biography of western snow-surveying, by J. E. Church.
(2) California cooperative snow-surveys: Snow-survey and precipitation data and seasonal forecast of stream-flow (April 1, 1933), by California Division of Water Resources.
(3) Seasonal snow-survey and forecast of stream-flow (April 1, 1933), Nevada Cooperative snow-surveys: (I) Central Sierra Quadrangle, by Forecast Committee in charge of cooperative snow-surveys; (II) Humboldt Quadrangle, by J. E. Church, Adviser, and Carl Elges, Assistant.

Other publications are the "Water-supply forecast for Utah, 1933" by George D. Clyde, Utah Agricultural Experiment Station, and "Snow-survey of Adirondack Region, New York, March 20-26, 1933" by E. S. Cullings, in charge, Watertown, New York. A bulletin is also issued by Oregon.

As promised last year, a complete list of all publications for each year will, so far as possible, be obtained and a collection made for purposes of loan.

Nevada Agricultural Experiment Station,
Reno, Nevada

ON GLACIERS

Francois E. Matthes, Chairman

In this its second annual report the Committee on Glaciers submits all the data it possesses concerning the variations in length of glaciers in the continental United States and Alaska in tabular form. This being the first tabulation, it has seemed desirable to include the records of past years as far back as they are known, so that there shall result as complete a foundation as possible, upon which the records of future years may be built.

In general, it has been the aim of the Committee to conform closely in this report to the simple and effective methods of tabulation employed by the Commission des Glaciers of the International Union of Geodesy and Geophysics. In a number of instances, however, explanatory notes have seemed necessary for the intelligent interpretation of the record; and in the case of the great Alaskan glaciers, whose large-scale oscillations are only imperfectly known from visits by exploring expeditions at irregular intervals, qualitative expressions often have been used instead of quantitative figures.

Special note has been made of every instance in which one of these glaciers was reported to be advancing into mature forest, the event having special significance as marking a maximum not attained for a long period previously. As might be expected, there is a rough synchronism between the extreme advances of several glaciers within the same district, but such synchronism of maxima is by no means general. Indeed, a

comparison of the records of Alaskan glaciers impresses one chiefly with the general lack of synchronism of glacier oscillations.

In Glacier Bay, for instance--to reach somewhat farther back into history than can be done in the tables--a great maximum seems to have occurred in the 18th century, following a period during which the glaciers were much smaller than today. Since that maximum the glaciers have melted back as much as 60 miles. On the other hand, at Lituya Bay, but a few miles to the northwest, the glaciers are now larger than in 1786, when La Pérouse visited that locality. In Yakutat Bay the glaciers have receded during the last century, and the same is true in the Copper River Basin. Yet farther to the northwest, in Prince William Sound, some of the glaciers are much larger today than they have been for the greater part of a century. The Yale and Smith glaciers appear recently to have passed their culmination, and the Harriman and Harvard glaciers, the trunk glaciers of Harriman and College fiords respectively, are still advancing into territory that has not been occupied by them for half a century or more.

Many of the figures given in the tables for recent oscillations of glaciers in the United States are question marked because the termini of those glaciers are so thickly mantled with residual débris that accurate measurements are impossible. They offer no clean ice-fronts to which to measure, and it is really a matter of conjecture just where those ice-bodies end.

Difficulties of this nature, but on a huge scale, have operated to frustrate the efforts of the officials of McKinley National Park, Alaska, to obtain measurements of the recession of the Muldrow Glacier, the longest ice-stream on the Alaska Range. The fact is, the lower end of this Glacier, for a distance of several miles, is stagnant and encumbered with residual débris. Some parts of it are covered with a growth of vegetation. No further attempts will be made to make definite measurements on this great ice-stream, but some of the smaller glaciers in its neighborhood that have fairly clean fronts will hereafter be measured annually.

With reference to the glaciers on the western mountain ranges in the United States it should be explained that all of them appear to have been in retreat for a number of years past. The record of the Nisqually Glacier, though probably not to be taken as an index for all of them (the Nisqually having southerly exposure, whereas the majority of glaciers on the western ranges have northeasterly exposures), nevertheless shows plainly that there have been no marked alternations of advance and retreat during the past 75 years--only continuous and fairly steady retreat. It is truly surprising, therefore, to find that during 1932 the glaciers on the Sierra Nevada of California either held their own or made decided advances. They are the only ones that did so, and the fact is to be attributed to the exceptionally heavy snowfalls that occurred in the Sierra Nevada during the winter of 1931-32. Evidently these excessive snowfalls were confined to that range and did not extend to the Cascade Range or the northern Rookies. Unfortunately reliable data on the snowfall at the high levels at which the glaciers lie are not available.

The retreat that has been general for a number of years among the glaciers on the western ranges of the United States is to be viewed broadly as part of a cycle that started from a maximum of glacier expansion about the middle of the nineteenth century. What is more, it is to be borne in mind that the great majority of the glaciers on our western mountain ranges very probably are not remnants of the great ice-bodies of the Pleistocene, or glacial epoch, but have come into existence only a few centuries ago, during a relatively frigid cycle that followed upon a prolonged period of mild, rainy conditions during which no, or only a very few glaciers existed on the ranges. The evidences upon which these rather revolutionary inferences are based were indicated in the Committee's report for 1931-32.

In the following tables the plus sign (+) indicates advance and the minus sign (-) indicates retreat of the glaciers.

Mount Rainier, Washington
(From data by National Park Service)

Glacier	1930-31	1931-32
	feet	feet
Nisqually	- 49	- 50
Emmons	-142(?)	- 18
Carbon		- 37
South Tahoma		- 37
Paradise		- (?)

Complete record of Nisqually Glacier
(* = Figures taken from historical records)

Epoch	Distance	Epoch	Distance
	feet		feet
1857-1885	- 760*	1924-1925	- 73
1885-1892	- 140*	1925-1926	- 86
1892-1918	-1310*	1926-1927	- 43
1918-1919	- 59	1927-1928	- 89
1919-1920	- 46	1928-1929	- 52
1920-1921	- 106	1929-1930	-118
1921-1922	- 67	1930-1931	- 49
1922-1923	- 44	1931-1932	- 50
1923-1924	- 83		

Mount Hood, Oregon
(Data by Research Committee, Mazamas)

Glacier	Epoch					
	1925-27	1927-28	1928-29	1929-30	1930-31	1931-32
			feet		feet	feet
Eliot	←		-40		→	No change
Coe			No change ←	-43	→	-19
Ladd		← Little change	→	-15(?)	→	No change

Yosemite National Park and
adjoining parts of the Sierra
Nevada, California
(Data by the National Park Service)

Glacier	Distance 1931-32
	feet
Lyell (west lobe)	+ 15(?)*
Lyell (east lobe)	+ 65(?)*
Maclure	+ 52(?)*
Dana	+ 40
Conness	+ (?)*
Kuna	+ (?)*
Koip	+ (?)*

*Owing to the heavy snowfalls that occurred in the Sierra Nevada during the winter of 1931-32 the glaciers remained covered with snow throughout the ensuing summer, and as a consequence the positions of the ice-fronts could not be determined with accuracy.

Glacier National Park, Montana
(Data from National Park Service)

Glacier	Distance 1931-32
	feet
Grinnell	-(?)
Blackfeet (west lobe)	-(?)
Blackfeet (east lobe)	-(?)
Sperry (Edwards lobe)	+(?)
Sperry (Gunsight lobe)	+(?)
Agassiz	

Early snowfalls in the autumn of 1932 made accurate measurements impossible.

Wind River Range, Wyoming
(Data from C. K. Wentworth)

Glacier	Distance 1906-1930
North Gannett	$-\frac{1}{2}$ to $-\frac{1}{4}$ mile
East Gannett	shrunk laterally
West Gannett	

Distances estimated with reference to positions shown on topographic map of 1906.

Glacier Bay, Alaska
(Data by Harry Fielding Reid and C. W. Wright)

Glacier	Epoch			
	1879-1892	1892-1906	1906-1929	1929-1931
	nau.mi.	nau.mi.	nau.mi.	nau.mi.
Muir	-1.8	-5.3	-6.2	+0.4
Adams[a]	-1.8	-3.5	-2.7	+2.2
Casement[a]	-1.8	← -7.2 →		+1.7
Plateau[a]	-1.8	← -5.5 →		+2.1
Carroll				-1.1
Rendu				-0.6
Grand Pacific	-3.2	-7.7	← -5.8 →	
Johns Hopkins	-4.9	-2.7	← -9.0 →	
Lamplugh[b]	-4.9	← -1.2 →		
Reid	-0.8	-0.4	← -0.7 →	
Hugh Miller	-1.5	-1.8	-1.6	+0.8
Charpentier	-2.2	-1.9	-1.8	+3.8(?)
Geikie	-1.3	-0.8	-0.4	-0.9
Wood	-1.2	-0.4	-1.5	+0.7

[a]Formerly a tributary of Muir Glacier. Measurements shown include tributary and Muir Glacier when they are united.

[b]Formerly a tributary of Johns Hopkins and Grand Pacific glaciers. Measurements shown include Lamplugh, Johns Hopkins, and Grand Pacific, when they were united.

Northern part of Prince William Sound, Alaska
(Data compiled by William Osgood Field, Jr.)

Glacier	18 ?-1892	1892-1899	1899-1909	1909-1911	1911-1914	1914-19 ?	19 ?-1931
Columbia							
West front	Advance invading mature forest	Recession interrupted by slight advance	+1200 ft	+500 ft	-25 ft	+125 ft	-900 ft

Glacier	18 ?-1892	1892-1897	1897-1908	1908-1910	1910-1914	1914-19 ?	19 ?-1931
Columbia							
Heather Island front	Advance invading mature forest	Recession and readvance	Recession	+742 ft	-30 ft	+200 ft	Recession followed by advance to within 250 ft of 1910 position
East front	.....						-1500 to -2500 ft
East terminus	.....						- 400 to - 800 ft

Glacier	1898-1910	1910 ---------- 1914	1914	1931
Valdez	Recession	← -708(Unmeasured advance 1905-1908) →	← -1240 ft →	
Shoup	← Front practically stationary but thickness greatly reduced →			

Glacier	1898-1899	1899-1905	1905-1909	1909-1910	1910-1914	1914-1925	1925-1931
Meares	← +1.5 miles →		← Advance invading mature forest →		← Advance of several hundred feet →		
Yale							
East margin	Little change	← +750 ft →			← +650 ft →		
Center	← Little change →						
Harvard		Little change	+600 ft	+100 to +150 ft	-20 ft	← +1300 to +1400 ft →	
			Invading mature alders				
Smith		← +600 ft →		Several hundred feet	Recession, shrinkage	← Advance followed by recession still in progress →	
Bryn Mawr		Little change	← +500 ft		Slight recession	← -1500 to -2000 ft →	
			Invading forest 50 years old →				
Vassar		Little change	← +500 ft →		?	← Marked recession →	
Wellesley	Recession	← Little change →		Advance	Recession	← Several hundred feet →	

Northern part of Prince William Sound, Alaska--Continued

Glacier	? - 1898	1898-1899	1899-1909	1909-1910	1910-1914	1914-1925	1925-1931
Barry	Advance into mature forest	-1/2 to -3/4 mile	-2.1 miles	E side -1600 ft W side -500 ft	E side -7000 ft W side -2000 ft	Recession	Little change

Glacier	18 ?-1899	1899-1905	1905-1909	1909-1910	1910-1914	1914-1925	1925-1931
Serpentine	-1/4 to -1/2 mile	Little change	-1/4 mile	← Little change →		← -2000 ft →	
Baker	Great advance	Slight recession	Little change	Advance	Slight recession	← Recession →	
Cataract	Maximum advance	← Little change →		Advance	Advance and slight recession	Recession back of 1909 position	Advance still back of 1909 position
Roaring	Advance?	Slight recession	← Slight advance →		Advance	← Slight recession →	
Harriman	Recession ?	← E side, -1050 ft → ← W side, no change →		E side, +1050 ft W side, +700 ft	Slight advance	E side advanced several hundred feet	+200 to +300 ft
Toboggan			+400 ft, then -625 ft	- 75 ft	← -832 ft →		

	18 ?-1899	1899-1900	1900-1909	1909-1910	1910-1914	1914-1925	1925-1931
Surprise	Advance	-0.1 mile	-1.1 mile	← Little change →		Recession	Recession

U. S. Geological Survey,
Washington, D. C.

ON EVAPORATION

George F. McEwen, Chairman

There has been no change in the membership of this Committee since its organization a year ago, and the tentative outline then prepared to serve as a guide for activities of the Committee met the general approval of the members. It is, of course, subject to revision in accordance with any suggestions offered.

The tentative outline pertaining to the work of the Committee as of last year is as follows: (1) Fundamental physical theories of evaporation and resulting formulae for computing evaporation; (2) practical formulae for estimating evaporation from available data on factors presumed to determine it, which formulae may be more or less empirical and subject to certain limitations, as to conditions and precision; (3) the

evaluation and interpretation of existing evaporation-measurements; (4) the kind of observations and the instrumental equipment for evaporation-investigations involving the important question of the standardization of methods; (5) information regarding persons or organizations conducting evaporation-investigations; (6) compilation of a comprehensive bibliography on evaporation; and (7) study of special problems, involving evaporation, that may be submitted by others in connection with either scientific investigations or engineering design.

Relative to item (7) of the outline, it is suggested that any member receiving requests for information send copies of the requests to the other members of the Committee in order that each member may know what is desired, and may have the opportunity to supply information according to his position and experience. Copies of such correspondence should be furnished the Chairman for filing and later summarization in the next report of the Committee. Before the formation of this Committee the Chairman has had correspondence relative to item (4), to the performance of artificial reservoirs in dissipating heat from condensers, and to cooling towers.

In response to a letter from the Chairman to members of the Committee and others, the following papers have been submitted for presentation at the meeting of the Committee on Evaporation, April 27 and 28, 1933: Clem A. Copeland, Research and Records Section, Bureau of Power and Light of the City of Los Angeles, California, A study in evaporation as affecting the runoff of Owens River, California, received April 14, 1933; Robert E. Kennedy, State Engineer of North Dakota, Bismark, North Dakota, Limitations of the Dalton factor in evaporation, received March 31, 1933.

Scripps Institution of Oceanography,
La Jolla, California

ON ABSORPTION AND TRANSPIRATION

Charles H. Lee, Chairman

The Committee's activities during the past year have been centered largely around the subject of transpiration and consumptive use. The outline of a proposed report on this subject was prepared, the purpose of which is to make available for research and practical workers in hydrology, engineering, agriculture, forestry, and as far as practicable in plant physiology, a brief statement of ascertained facts regarding the process of transpiration and the factors which control it, together with a summary of quantitative experimental work which has been done in the United States. The outline accompanies and is presented as a part of the Committee's report.

Material as submitted herein has been compiled under the last sub-heading of the outline, namely, "(6C) Quantitative experimental work--consumptive use." During the coming year it is proposed to complete a report in accordance with the outline, which will be submitted at the April 1934 meeting.

The Committee, in addition to its work on the subject of transpiration, has compiled a list of agencies in the United States carrying on work in the field of hydrology covered by the Committee, with brief information regarding their work and publications. This was done in accordance with the action taken at the meeting of California members of the Section of Hydrology, American Geophysical Union, held at Berkeley, California, November 5, 1932. The list is submitted with this report.

Consumptive use

The material assembled by the Committee during the past year consists of a list of consumptive-use determinations for specific varieties of natural and cultivated vegetation. It is classified under vegetational type so as to show the gaps in investigational work.

The list is confined to consumptive-use determinations, that is, those in which the combined loss by plant-transpiration and evaporation from the surrounding soil was measured. Pure transpiration, water-requirement, duty of water, etc., are not included. The members of the Committee desire to have the list complete, and will welcome information regarding any determinations which have been omitted.

Vegetational types are classed as either natural or cultivated, weeds being included with the latter. Natural vegetation is further divided into western with semi-arid climatic conditions, and eastern with humid conditions.

Natural vegetation (Western)

Coniferous forest--No determinations.

Woodland on slopes--No determinations.

Woodland on bottom lands--Cottonwood and mesquite trees deriving water-supply from a capillary fringe in San Pedro Valley, Arizona. Observations made from 1916 to 1922, consisting of continuous graphs of water-level in adjacent shallow wells registering fluctuations of the surrounding water-table. It was demonstrated that the daily decline of the water-table was due to withdrawal of ground-water from the zone of saturation by the trees. The work was carried on by the University of Arizona under the direction of G. E. P. Smith, Professor of Irrigation Engineering. Results are unpublished, but were described in a paper given before the Geological Society of Washington, November 22, 1922.

Willow trees deriving water-supply from a capillary fringe in bottoms of Mokelumne River, near Lodi, California. Observations during summer of 1932 using water-table fluctuations method. The work was carried on by the United States Geological Survey and East Bay Municipal Utility District. Results are unpublished.

Willow trees deriving water-supply from a capillary fringe near Santa Ana, California. Observations commenced in 1931 and still in progress. Trees were grown in isolated tanks 6 feet in diameter, 3 feet deep set in ground, and water measured as supplied at bottom. Work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California. Results will be published in bulletins of the United States Department of Agriculture and the State of California, Department of Public Works, Division of Water Resources.

Woodland on stream borders--Willow, alder, and miscellaneous stream-border vegetation deriving water-supply from stream-flow or direct seepage therefrom along the following streams in southern California: Devils Canyon; Coldwater Canyon; Mohave River; Temescal Creek. Determinations by measuring inflow and outflow from a selected section of stream-channel with bedrock-control at gaging-points. Check observations by means of isolated 2-foot diameter, 30-inch depth tanks surface-flooded, are being carried on at Temescal Creek. Work being carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California. Results will be published with results of tank observations on willows.

Shrubs--Chaparral and sage brush deriving water-supply from precipitation (wet winter - dry summer) in San Bernardino County, California. Observations were commenced in the season of 1927-28, and consist of soil-moisture measurements in field-plots. The work is carried on by the Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture. Preliminary results are published in Bulletin 33, Division of Water Resources Department of Public Works, State of California, 1930. Final data will appear in State and United States Department of Agriculture bulletins.

Creosote, etc.: No determinations.

Greasewood and alkali resistant shrubs, deriving water-supply from a capillary-fringe in Escalante Valley, Utah. Observations made in 1925, 1926, 1927, consisting of continuous graphs of water-level in adjacent shallow wells registering fluctuations of the surrounding water-table. A method was developed for interpreting daily fluctuations in terms of ground-water consumed by the plants plus soil-evaporation. The work was carried on by the United States Geological Survey. Results are published in Water Supply Paper 659-A, United States Geological Survey, 1932.

Grassland--Bunch grass: No determinations.

Short grass deriving water-supply from precipitation in the Great Plains at Burlington, Colorado (altitude 4,160 feet). Observations July 5 to 20, 1923. Unbroken sod and soil was placed in tanks 12 inches in diameter and 3 feet deep, and set flush in the ground without injuring the closely surrounding grass. Precipitation and

water artificially applied upon the surface were measured and total consumptive use for the growing season was computed from the average daily rate. Work carried on by J. E. Weaver and John W. Crist of the University of Nebraska. Results published in Ecology (v. 5, No. 2, April 1924).

Semi-desert grass: No determinations.

Mountain meadows: No determinations.

Swamp and marsh: Tule (scirpus) and cat-tail (typha) growing with roots submerged in fresh water at least during a part of the season and deriving water-supply therefrom in southern California near Santa Ana, and in the delta of the Sacramento-San Joaquin rivers in central California. Observations commenced in 1929 and still in progress. Plants grown in isolated tanks 25 inches in diameter, 2.7 feet deep near Santa Ana, and in 2-feet diameter, 5-foot depth tanks both isolated and closely surrounded by similar vegetation in the Delta. Water applied by surface-flooding. Work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California. Preliminary results published in Bulletin No. 33, and Sacramento-San Joaquin Water Supervisors Report for year 1931, of Division of Water Resources, Department of Public Works, State of California. Observations have also been made upon tule at Mud Lake, Idaho, during the growing season of 1921, 1922, and 1923. Plants were grown in a 4-foot by 4-foot tank surrounded by vegetation. Water applied by surface-flooding. Work carried on by United States Geological Survey and results published in Water Supply Paper 560-D, United States Geological Survey, 1925.

Foothill annuals in southern California deriving water-supply from precipitation. Observations during 1927, 1928, 1929, 1930, consisting of soil-moisture determinations and precipitation at field-plots. Work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture. Results published in Bulletin 33, Division of Water Resources, Department of Public Works, State of California.

Alkali-resistant salt grass deriving water from a capillary-fringe. Observations in Owens Valley, California, 1909, 1910, 1911, and in southern California beginning in 1929. Unbroken sod and uninjured surrounding grass in both experiments, soil broken in excavation and replacement in Owens Valley experiments, but not in southern California. Tanks 7-1/2 feet deep, 9-3/4 feet deep in former and 23 inches diameter and 3.3 feet deep in latter. Water applied at bottom in both experiments. Owens Valley work carried on by City of Los Angeles, Bureau of Los Angeles Aqueduct, and United States Geological Survey, and results published in Water Supply Paper 294, United States Geological Survey and more completely in Transactions, Amer. Soc. C. E. (v. 78, p. 148, 1915). Southern California work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California, and preliminary results published in Bulletin No. 33, Division of Water Resources, Department of Public Works, State of California.

Alkali-resistant bermuda grass deriving water from a capillary-fringe in southern California. Observations beginning in 1929. Work carried on and published by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, as for salt grass.

Alkali-resistant salt grass deriving water from a capillary-fringe in Escalante Valley, Utah. For details see "greasewood and alkali-resistant shrubs."

Natural vegetation (Eastern)

Coniferous forest--No determinations.

Hardwood or broadleaf forest--No determinations.

Grassland--Prairie grass of the tall-grass sod type deriving water-supply from winter and summer precipitation at Lincoln, Nebraska. Observations July 24 to August 8, 1923. Work carried on by J. E. Weaver and John W. Crist of the University of Nebraska, following same procedure as for short grass previously described. Observations were also made on mixed prairie, consisting of both tall and short grasses, at Phillipsburg, Kansas. Results published in Ecology (v. 5, No. 2, April 1924).

Swamp and marsh: No determinations.

Grass in timber: No determinations.

Cultivated vegetation

Orchard trees--Citrus, including avocado, in San Diego County, California, deriving water supply from winter precipitation and surface-irrigation. Observations during

1926 and 1927 consisting of soil-moisture determinations at field-plots with measurement of precipitation and irrigation-water. Work carried on in cooperation with Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, and Agricultural Experiment Station, University of California, Berkeley, California. Results published in Bulletin 489, Agricultural Experiment Station, University of California.

Citrus and walnuts in Los Angeles County, California, deriving water-supply from precipitation and surface-irrigation. Observations during 1927, 1928, 1929, and 1930, consisting of soil-moisture determinations at field-plots in conjunction with measurements of precipitation and irrigation-water applied. Work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture. Results unpublished.

Citrus on Yuma Mesa, Arizona, deriving water-supply from irrigation. Observations beginning in 1929 and still in progress. Measurements consist of field-moisture determinations and measurements of irrigation-water at field-plots. Work carried on by Arizona Agricultural Experiment Station, Tucson, Arizona. First progress-report published by the Experiment Station as Technical Bulletin No. 37.

Deciduous, consisting of peach, prune, apricot, and almond trees in Sacramento Valley, California, deriving water-supply from winter precipitation and surface-irrigation. Observations 1924 to 1928 with measurements of soil-moisture, precipitation and irrigation-water applied at selected farm tracts. Work carried on by California Agricultural Experiment Station, University of California, Berkeley, California. Results unpublished.

Vines--Grape vines in Sacramento Valley, California, deriving water-supply from winter precipitation and irrigation. See "deciduous orchard trees" for details.

Annual field-crops--Beets, potatoes, corn, wheat, oats, barley, peas, beans, clover, deriving water-supply from precipitation and surface-irrigation. Observations of precipitation and irrigation-water at field-plots from which deep percolation was considered as negligible in amount. Work carried on from 1902 to 1919 by Utah Agricultural Experiment Station in Cache Valley, Utah, and during 1914, 1915, and 1916 by Twin Falls Agricultural Experiment Station in Snake River Valley, Idaho. Results published in annual reports of the experiment stations. See especially, Bulletin 173, Utah Agricultural Experiment Station and 1919 Annual Report of Twin Falls Agricultural Experiment Station. Also paper on "Consumptive use of water in irrigation" by Duty of Water Committee of the Irrigation Division (Trans. Amer. Soc. C. E., v. 94, p. 1349, 1930).

Beans, beets, corn, grain, onions, potatoes, deriving water from precipitation and sub-irrigation through peat-soil in the Delta of the Sacramento-San Joaquin rivers, California. Observations commenced in 1924 and still in progress using isolated tanks 2 feet in diameter and 5 feet deep, with unbroken soil-column. Water applied at bottom of tanks. Work carried on by Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California. Results published by Division of Water Resources, Department of Public Works, State of California, in Annual Reports of Sacramento-San Joaquin Water Supervisor.

Perennial field-crops--Alfalfa, deriving water-supply from precipitation and surface-irrigation. Observations of precipitation and irrigation-water at field-plots from which deep percolation was considered as negligible in amount. See "annual field-crops" at same location for details.

Asparagus and celery deriving water-supply from precipitation and sub-irrigation through peat-soil in Delta of Sacramento-San Joaquin Rivers, California. See annual field-crops at same location for details.

Alfalfa deriving water-supply from a capillary-fringe in Escalante Valley, Utah. Observations made in 1925, 1926, 1927, consisting of continuous graphs of water-level in adjacent shallow wells registering fluctuations of the surrounding water-table. A method was developed for interpreting daily fluctuations in terms of ground-water consumed by the plants plus soil-evaporation. The work was carried on by the United States Geological Survey. Results are published in Water Supply Paper 659-A, United States Geological Survey, 1932.

Garden truck--No determinations.

Weeds--Weeds deriving water-supply from precipitation and sub-irrigation through peat-soil in Delta of Sacramento-San Joaquin rivers, California. Observations 1930, 1931, 1932, at isolated tanks 2 feet diameter, 5 feet depth supplied with water at bottom. See "annual field-crops" at same location for details.

Weeds mixed with grass deriving water-supply from precipitation in southern California. See reference above under "Foothill annual grasses."

Future work

The preparation of bibliographies and standard definitions pertaining to the subjects of absorption and transpiration, is still in progress, and work will be continued during the coming year. This, together with the completion of the report on transpiration, will fully occupy the membership of the Committee during the coming year.

58 Sutter Street,
San Francisco, California

OUTLINE OF PROPOSED REPORT OF COMMITTEE ON ABSORPTION AND TRANSPIRATION ON PLANT-TRANSPIRATION AND CONSUMPTIVE USE

(1) Definitions

(2) The physical process of transpiration: (a) Water-absorption by roots; (b) transmission to membranes from which evaporation occurs; (c) cuticular transpiration; and (d) stomatal transpiration.

(3) Factors controlling the rate of plant-discharge by transpiration: (a) Physiological; (b) environmental including (1) above soil (or water) surface and (2) below soil (or water) surface; and (c) relative importance of various factors.

(4) Methods of measuring plant-discharge by transpiration: (a) Potometer (end of severed plant or branch in sealed vessel of water); (b) phytometer (growing plant in sealed pot or tank); (c) cobalt chloride; (d) Freeman method; and (e) rate of moisture-loss from freshly cut plants determined by weighing.

(5) Methods of measuring consumptive-use: (a) Single plant or type of vegetation including (1) tank or pot (unsealed) and (2) experimental field-plot; (b) agricultural crops in irrigation-projects or valleys including (1) measuring percolation-loss from irrigated land by determining annual increase in spring or seepage flow below tract, (2) net depletion of river-water by irrigated lands drained either naturally or artificially, (3) relation of aggregate irrigation-diversion to change in level of ground-water, (4) soil-moisture determinations before and after irrigation, (5) application of results of tank or field-plot experiments to classified acreage with similar climatic and soil-conditions, and (6) relation of available heat to consumptive use; (c) agricultural or mixed vegetation in valleys including (1) adaptation of methods developed in ground-water hydrology for quantitative estimating of ground-water supplies; (d) mixed vegetation in stream drainage-areas including (1) graphical method based on rainfall-runoff relation (Grunsky, Rafter, Lee, etc.), (2) rational method using formula (Russell, Vermuele, Justin, etc.), and (3) rational method by computation from rainfall and other physical data (Meyer); (e) vegetation with roots in capillary-fringe including (1) method by interpretation of continuous records of fluctuation of water-table.

(6) Quantitative experimental work--

(A) Relation of water-loss by cuticalar and stomatal transpiration to total plant-discharge.

(B) Total plant-discharge by transpiration.

List under vegetational type and describe under following sub-headings all published or current work, principally by botanists and foresters

Main headings (vegetational type)

(1) Natural vegetation including (a) Western (semi-arid climate) for (1) forest under coniferous and woodland (on stream-borders, bottom-lands, and slopes); (2) shrub under chaparral, sagebrush, creosote

(mixed desert shrubs), and greasewood and alkali-resistant shrubs; (3) grassland (grass-like plants and herbs) under bunch grass, short grass, semi-desert grassland (southwest), mountain meadows, swamp and marsh vegetation (rush, sedge, reed, etc.), foothill annuals (Pacific Coast), and alkali-resistant grass (salt grass, etc.); and (b) Eastern (humid climate) for (1) forest under coniferous and hardwood or broad leaf; (2) grassland for prairie, swamp and marsh (rush, sedge, reed, etc.), and grass in timber (understory of grasses and herbs).

(2) Cultivated vegetation including (a) orchard trees (citrus, deciduous, etc.); (b) vines (grapes, climbing berries, etc.); (c) annual field-crops (corn, potatoes, etc.); (d) perennial field crops (alfalfa, etc.); (e) garden-truck; and (f) weeds.

Sub-headings (description)

(1) Water-supply including (a) precipitation for (1) winter maximum - summer minimum, (2) winter minimum - summer maximum, and (3) two maxima, winter and summer; (b) shallow water-table; (c) flowing stream; (d) swamp or marsh; (e) surface-irrigation; and (f) salt marsh, desert playa, etc.

(2) Location.

(3) Inclusive dates of observation.

(4) Period of observation for (a) hour, (b) day, (c) week, (d) month, and (e) year.

(5) Method of observation including (a) equipment and (b) application of water.

(6) Authority.

(7) Published reference.

(C) Consumptive use (plant-discharge by transpiration plus evaporation from surrounding soil).

List and describe under same headings as above all published or current work, principally by engineers and agricultural investigators.

LIST OF AGENCIES IN THE UNITED STATES CARRYING ON WORK IN THE FIELD COVERED BY THE COMMITTEE ON ABSORPTION AND TRANSPIRATION, WITH BRIEF INFORMATION REGARDING THEIR WORK AND PUBLICATIONS

(Prepared by Committee on Absorption and Transpiration, Section of Hydrology, American Geophysical Union)

Absorption

(1) Division of Irrigation, Bureau of Agricultural Engineering, United States Department of Agriculture, Berkeley, California.

(a) Field-tests of rates of absorption of flood-waters of torrential streams spread at experimental plots in southern California, beginning with winter season of 1929-1930. Preliminary results published by State of California, Department of Public Works, Division of Water Resources, in Bulletin No. 32, South Coastal Basin, 1930. Final results will probably be published by United States Department of Agriculture in a technical paper or bulletin.

(b) Field-tests of absorption from rainfall (rainfall-penetration) by valley-lands under semi-arid conditions in San Bernardino, Riverside, Orange, Los Angeles, and Ventura counties, California. A new method has been developed consisting of frequent soil-moisture determinations to a depth below the root-zone at selected plots in typical soils, vegetation, and surface-treatment, coupled with measurements of rainfall, runoff, and depth of penetration. Work commenced with the season of 1927-28. First progress-report published by State of California, Department of Public Works, Division of Water Resources in Bulletin No. 33. Future reports will be published by the United States Department of Agriculture and in various technical journals and society publications.

(2) Department of Interior, United States Geological Survey, Division of Ground-Water, Washington, D. C.

Experimental study of absorption from precipitation under semi-arid conditions (wet and dry season) at various points in western United States using both the improved form of lysimeter (in southwestern Texas) and the new soil-

moisture method developed by the Bureau of Agricultural Engineering, United States Department of Agriculture. Intensive observations have been in progress near Lodi, California, principally on Hanford fine sandy loam-soil since the season 1929-30, and also in southwestern Texas, on the outcrop of the Carrizo sandstone in the Winter Garden district. Results, as yet unpublished, will appear in Water Supply Papers of the United States Geological Survey.

(3) California Forest Experiment Station, Forest Service, United States Department of Agriculture, Berkeley, California.

(a) Seepage-runoff relations at Berkeley. To isolate experimentally the influence of litter, various types of vegetative cover and other factors, on surficial runoff and seepage of natural and artificial precipitation. (1) Five tank-lysimeters; 2.8 by 7 by 3 feet with soil slope of 30 per cent, fitted to employ artificial rain, and to measure surficial runoff, seepage, and erosion. (2) Ten large chaparral lysimeters, with dimensions of 6 by 13.3 by 4 feet with slope of 27.5 per cent.

(b) Surficial runoff and erosion. To measure, by means of plot-installations, the influence of chaparral and other vegetative cover, in place, on surficial runoff and erosion from natural precipitation. Bordered plots, approximately 1/40 acre in size, equipped with automatic recording instruments and arranged in duplicate pairs, one pair denuded by burning, one pair with vegetation intact; three series of 4 plots each in southern California chaparral, one series of 6 plots in coastal chaparral at Berkeley, one series of 6 plots in the pine region at Northfork.

(c) Watershed-studies. To determine the influence of chaparral vegetation on surficial runoff, stream-flow, water-yield, and erosion as they affect flood-control and conservation of water for irrigation and urban use; and further to determine feasible methods of management of watersheds through manipulation of vegetation and control of erosion for flood-control and for maximum beneficial water-production. One 44-acre watershed (Barrance) to develop methods of measuring silt-laden water and to study vegetative succession following the 1925-burn. An experimental forest of 13,000 acres in San Dimas and Big Dalton canyons in which are being concentrated comprehensive studies of watershed-relationships as stated above. Within the forest two series of triplicate watersheds of 70 to 120 acres each are now being equipped with control-dams, rain-gages, and recording-instruments. After several years' observation to determine the runoff-coefficient of each of the six small watersheds, two of the watersheds in each triplicate series will be burned off, one being allowed to revegetate naturally and the other being kept bare by periodic burning, while the third will be left in its natural state. Experimentation is planned to continue for 15 years or longer.

(d) Erosion and erosion-control studies throughout California, including measurement of sedimentation in reservoirs following fire in their watersheds; artificial revegetation of burned watersheds to minimize soil-erosion; fixation of disturbed soil on forest highway projects for the protection of reservoirs and water-spreading grounds. Preliminary results published by State of California, Department of Public Works, Division of Water Resources, in Bulletin No. 32, and by Water Conservation Committee, Irrigation Division, American Society of Civil Engineers (Mimeograph report of Conference on Research Problems in Consumptive Use of Water and Conservation of Rainfall at Los Angeles, California, March 27 to 29, 1930). Progress and final results will be published in various technical articles, technical society proceedings, and the bulletins and papers of the United States Department of Agriculture.

(4) Central States Forest Experiment Station, United States Department of Agriculture, Columbus, Ohio.

A study to determine the effect of litter upon porosity of soil under different conditions developed by cutting, fire, grazing, and plantations. Laboratory and field experiments with 1,600 soil-samples from 22 old-growth forest sites in Ohio, Indiana, Illinois, and Michigan; 36 second-growth woods in Ohio, representing grazed and ungrazed conditions; and 13 forest plantations in Ohio and Illinois. Nearly 1,000 field-tests for water-absorption by the soil were made on the same sites. Manuscript submitted to the Washington office for publication.

(5) Appalachian Forest Experiment Station, Forest Service, United States Department of Agriculture, Asheville, North Carolina.
Experimental study of relation of different types of vegetation-cover, forest-fires, and removal of natural organic cover upon absorption and storm-flow at permanent field-plots in the southern Appalachians. Results unpublished, but will eventually appear in Technical Bulletins and other publications of the United States Department of Agriculture.

(6) Intermountain Forest and Range Experiment Station, Forest Service, United States Department of Agriculture, Ogden, Utah.
Detailed experimental study during past 18 years of range grasses upon surface-runoff and soil-erosion from natural watersheds in Intermountain Region of western United States. Progress-results published in Technical Bulletin No. 220, United States Department of Agriculture.

(7) Division of Water Resources, Department of Public Works, State of California, Sacramento, California.
Experimental study of absorption from flood-waters of torrential streams in natural channels and on selected spreading grounds in the South Coastal Basin embracing watersheds of Los Angeles, San Gabriel, and Santa Ana rivers, in Los Angeles, San Bernardino, and Riverside counties, California. The purpose of the investigations is to furnish data for design of works for more complete conservation of local waste-waters and utilization of imported waters. Preliminary outline of work published by State of California, Department of Public Works, Division of Water Resources, in Bulletin No. 32.

(8) City of Los Angeles, Department of Water and Power, Bureau of Water Works and Supply, Los Angeles, California.
Field-tests of rates of absorption from controlled flows of clear water in prepared basins at 300-acre tract in San Fernando Valley, Los Angeles County, California. Scientific studies are being made of the effect of temperature, silt, etc., upon the rate of absorption, and also the effect upon the water-table, etc. Experimental work commenced with the winter season of 1929-30 and has become the basis for utilization of the entire tract for placing surplus winter-flow from the Owens River Aqueduct in underground storage for later recovery for municipal water-supply. Results are unpublished.

(9) Los Angeles County Flood-Control District, Los Angeles, California.
Experimental study of rates of absorption from flood-waters of regulated torrential streams in natural channels on selected spreading grounds in Los Angeles County, California, for the purpose of obtaining data for design of comprehensive flood-control and water-conservation works for a district covering 2,800 square miles of which one-half is mountain watershed (150 separate drainage areas) and one-half intensively developed suburban and urban property. Preliminary outline of work published by State of California, Department of Public Works, Division of Water Resources, in Bulletin No. 32, South Coastal Basin, 1930. Progress-reports published in various technical journals and proceedings of technical societies.

(10) American Society of Civil Engineers, 33 West 39th Street, New York.
General studies of absorption of water from precipitation and stream-flow, based upon experimental data obtained from various sources. Published in Proceedings and Transactions of the Society. See paper entitled "Water-supply from rainfall on valley-floors" by A. L. Sonderegger, with discussion in Transactions American Society of Civil Engineers (v. 94, p. 1242, 1930). Other papers are in preparation by members of the Water Conservation Committee, Irrigation Division of the Society. General studies of relation of forests and stream-flow based upon experimental data obtained from various sources. Published in Proceedings and Transactions of the Society. See recent paper entitled "Forests and stream-flow" by W. G. Hoyt and H. C. Troxel in August 1932 Proceedings, with discussion in succeeding issues closing in May 1933.

(11) Agricultural Experiment Station, College of Agriculture, University of Arizona, Tucson, Arizona.

Experimental study by soil-moisture method of absorption of water from surface-irrigation, especially for Yuma sand soil on Yuma Mesa, Arizona. Progress-reports published as Technical Bulletins of the Experiment Station (see Technical Bulletin No. 37, 1931).

(12) Division of Irrigation Investigations and Practice, College of Agriculture, University of California, Berkeley, California.

Experimental study by soil-moisture method of absorption of water from surface-irrigation at various locations throughout California, including a wide variety of soil-types, crop, and method of irrigation. Investigations consist of research to determine underlying principles and quantitative results. Published results to be found in Hilgardia, and the Bulletins and Technical Papers of the University of California, Agricultural Experiment Station, Soil Science, etc.

Transpiration

(1) Division of Agricultural Engineering, United States Department of Agriculture, Berkeley, California.

(a) Experimental studies of consumptive use of water by agricultural plants and natural vegetation in progress at various experiment stations in the western part of the United States, in cooperation with state agricultural experimental stations and other state agencies, for the past 30 years with progressive improvement in methods, refinement, and accuracy of results. Investigations now consist of research to determine principles underlying soil-, water-, and plant-relationships, and quantitative determination of consumptive field-requirements. Both tank and field-plot methods are being used and recent tests include a great variety of orchard, field, and truck crops, as well as natural vegetation such as weeds, brush, natural grasses, stream-border vegetation, and aquatic vegetation, such as tule. The following are cooperating state experiment stations: (1) University of Arizona, College of Agriculture, Agricultural Experiment Station, Tucson, Arizona; (2) University of California, Division of Irrigation Investigations and Practice, College of Agriculture, Berkeley, California; (3) Colorado Agricultural College, Agricultural Experiment Station, Ft. Collins, Colorado; (4) University of Idaho, Idaho Agricultural Experiment Station, Boise, Idaho; (5) New Mexico College of Agriculture and Mechanic Arts, Agricultural Experiment Station, State College, New Mexico; (6) Oregon Agricultural College, Agricultural Experiment Station, Corvallis, Oregon; (7) State Board of Water Engineers, Austin, Texas. Published results to be found in the Technical Bulletins, Professional Papers, and Bulletins of the United States Department of Agriculture, Bulletins and other publications of cooperating State Agricultural Experiment Stations, and Bulletins of other State agencies. In this connection, see California State Department of Public Works, Division of Water Resources Bulletin No. 33, 1930, and others to be issued.

(2) Bureau of Plant Industry, United States Department of Agriculture, Washington, D.C.

Experimental studies of transpiration-rate and water-requirements of agricultural plants and weeds. Determinations of the latter made by growing plants in pots or tanks and measuring water absorbed during growth and weight of dry matter produced. Published results in bulletins of Bureau and Journal of Agricultural Research.

(3) Division of Irrigation Investigations and Practice, College of Agriculture, University of California, Berkeley, California.

Experimental studies of water-requirements of agricultural plants in progress at various points in California for the past 20 years, with progressive improvement in methods, refinement, and accuracy of results. Investigations now consist of research to determine principles underlying soil-, water-, and plant-relationships, and quantitative determination of consumptive field-requirements. Both tank and field-plot methods are being used, and tests include a great variety of orchard, vineyard, field, and

truck crops. Published results to be found in Hilgardia, A Journal of Agricultural Science; the Bulletins and Technical Papers of the University of California, College of Agriculture, Agricultural Experiment Station, Berkeley, California; Soil Science; Plant Physiology; Proceedings and Papers of the First International Congress of Soil-Science; and Transactions of the American Society of Agricultural Engineers; etc.

(4) Utah Agricultural College Experiment Station, Logan, Utah.
Quantitative determination of yield and consumptive use for alfalfa and annual field-crops in field-plots. Work commenced in 1902 and has been carried on almost continuously with progressive improvements. Results published in Bulletins of the Experiment Station (see especially No. 173 for a summary of results up to 1920).

(5) Department of Interior, United States Geological Survey, Division of Ground-Water, Washington, D. C.
Experimental study of discharge from ground-water in the zone of saturation by transpiration of plants, as determined from continuous records of water-level fluctuations in shallow wells and fluctuations in dry-weather stream-flow. Also quantitative transpiration from tule and other aquatic plants grown in tanks. Results published by United States Geological Survey in Water Supply Papers (see especially Nos. 659-A and 560-D).

(6) Department of Botany, University of Nebraska, Lincoln, Nebraska.
Experimental study of the relation of available moisture to vegetation-type prairie and woodland in Nebraska and adjacent states, and determination of transpiration from range grasses of western plains, using tanks with unbroken sod and soil surrounded by natural vegetation. Results published by J. E. Weaver, Professor of Plant Ecology, and others in Ecology, Carnegie Institution of Washington publications, University of Nebraska Bulletins, etc.

(7) Laboratory of Plant Physiology, The Johns Hopkins University, Homewood, Baltimore, Maryland.
Experimental study of water-relations of plants with particular reference to physical physiology, including soil-moisture as the source of water-supply for ordinary plants, water-absorption by roots, and water-excretion by glands, etc. Results published by Burton E. Livingston, Director, Laboratory of Plant Physiology and others in Johns Hopkins University Circulars, Plant World, Carnegie Institution of Washington Year Books, Plant Physiology, etc.

(8) University of Arizona, College of Agriculture, Agricultural Experiment Station, Tucson, Arizona.
Quantitative determination of consumptive use for cottonwood trees in San Pedro Valley, Arizona. These trees derived their supply from ground-water and determinations were made from continuous records of water-level fluctuations in shallow wells. This was the first known instance of the use of this method. Quantitative studies of consumptive use from citrus trees by soil-sampling and moisture-determinations. Work carried on at Yuma Mesa, Arizona, and commenced in 1930. Results published in technical bulletins of Arizona Agricultural Experiment Station (see No. 37, etc.)

(9) American Society of Civil Engineers, 33 West 39th Street, New York.
General studies of effect of changes of forest and brush-cover upon stream-flow based upon experimental data obtained from various sources. Published in Proceedings and Transactions of the Society. [See Trans. Amer. Soc. C. E., v. 62, pp. 245-546; v. 81, pp. 1218-1310; v. 94, pp. 1294-1301; and Proceedings Amer. Soc. C. E., August 1932 to May 1933, paper and discussion on "Forests and stream-flow."]

(10) California Forest Experiment Station, United States Forest Service, Berkeley, California.
Experimental study of loss of stream-flow in southern California streams by transpiration from riparian vegetation. Installation at Devils Canyon in cooperation with Irrigation Division of Bureau of Agricultural Engineering.

Evaporation-transpiration. Measurement of water-losses from soils through evaporation and transpiration and other factors influencing such losses. At Devil Canyon 12 "rain-retention" pans, 4 lysiphytometers; at Berkeley 2 evaporation-pans; at Northfork 6 retention-pans, 2 lysiphytometers, 2 evaporation-pans. Publication of results in bulletins and papers of United States Department of Agriculture.

(11) Kansas State Agricultural College, Kansas Agricultural Experiment Station, Manhattan, Kansas.
Experimental studies of various phases of transpiration from agricultural crops. Published results in Technical Bulletins of the Experiment Station; Plant Physiology by Edwin C. Miller, Professor of Plant Physiology, published by McGraw-Hill Book Company, 1931; etc.

(12) Carnegie Institution of Washington, Department of Botanical Research, Washington, D. C.
Experimental studies of various phases of transpiration, especially from desert vegetation in vicinity of Desert Botanical Laboratory, Tucson, Arizona. Results published by D. T. MacDougal and others in Carnegie Institution publications and various technical botanical society publications and journals.

ON RUNOFF

LeRoy K. Sherman, Chairman

The outstanding work of the Committee on Runoff during the past year is a paper entitled "Rainfall, runoff, and evaporation." This work was under the joint supervision of Robert E. Horton and the Committee Chairman, L. K. Sherman. It is a comprehensive review of the recent works of many American hydrologists, special articles by members of the Committee, and summarized conclusions by the supervising editors. The work is grouped under the following topics:

(I) Rainfall data--Development of the rainfall-, intensity-, duration-, frequency-curves.
(II) Stream-flow and runoff data with contributions by Pierce, Pritchett, Merriam, and Merryfield.
(III) Frequency of runoff-rates--A review of studies and application of the laws of mathematical probability.
(IV) Peak runoff-rates, due to concurrent storms, by empirical methods and formulae.
(V) Peak runoff-rates, due to concurrent storms, by the rational method, including a special contribution by Horner on "Runoff from urban areas."
(VI) Average runoff-rates, monthly, seasonal, or annual. Prior's check on the reliability of formulas; comments and a suggested procedure by Horton; abstract of a thesis by Collins and Snyder.
(VII) Average runoff-rates per square mile--Data on the Connecticut River Basin by Barrows and comparison with data on the Illinois River Basin by Sherman.
(VIII) Distribution of runoff-rates, due to concurrent storms by analysis of hydrographs. Progress in the computation of hydrographs of runoff. (In this connection, we wish to refer to the recent work of Mr. Bernard who has been preparing a paper on the rainfall-runoff relation which presents a further development of some of the principles presented by the Committee on Floods of the Boston Society of Civil Engineers and by L. K. Sherman.)
(IX) The author's résumé and conclusions. Time here is not permitted for a final review of the conclusions by all members of the Committee as yet. The following conclusions are offered tentatively. They represent solely the opinions of Messrs. Sherman and Horton at present.

Author's résumé and conclusions

(1) Data and expressions for the intensity, duration, and frequency of rainfall have been developed to a fair degree of reliability for many localities in the United States.

(2) There is a material divergence in the recorded depths of identical rainfall between observation taken on the ground and on the top of adjacent buildings. The observed divergence is progressive with change in elevation. The Weather Bureau should evaluate and apply a coordinating factor to rainfall-observations taken at different local elevations above the ground.

(3) In the study of rainfall-runoff it would be convenient if the published records of rainfall were geographically grouped according to their drainage-basin location.

(4) The application of the principle of skew-frequency to rainfall- and runoff-data is useful and reliable within limits. The basic formula must operate between finite limits.

(5) The empirical formulae for estimating peak- or flood-rate of runoff from rainfall are in general use for making approximate estimates for engineering purposes. These formulae are useful when applied with experienced judgment and full knowledge of their derivation, limitations of range and location, and when used in analogy with pertinent stream-flow records.

(6) The empirical formulae are of little value as a scientific expression of the laws relating to the relationship of runoff and rainfall.

(7) The rational method for computing peak-rates of runoff from rainfall is in general use for application to small areas served by artificial conduits. The rational method has superseded the use of the empirical formulae for this purpose.

(8a) Based upon a uniform distribution of effective rain over the drainage-basin the time of concentration on natural drainage-basins can be determined by noting the time-interval between beginning of the storm and the appearance of the peak-rate of runoff, provided the duration of the storm equals or exceeds the true concentration-time. Without this proviso the rule is erroneous.

(8b) The time-interval of the falling stage of a hydrograph of runoff due to an effective rainfall is practically a constant for a given basin provided the base-flow is a constant.

(8c) Under the foregoing conditions the period of duration of runoff from a given basin is equal to the duration of effective rainfall plus a constant.

(9) The formulas and procedures now developed for mean annual or monthly runoff are not reliable for any general application.

(10) An application of the method suggested by Horton under topic VI for expressing the relation between average season rainfall and runoff should be made. This study should be applied to a number of different drainage-basins which have good rainfall- and runoff-records available.

(11) The average seasonal runoff per square mile decreases towards the lower sections of most drainage-basins. With flat topography the average runoffs per square mile are quite uniform during identical seasons. The seasonal runoff per square mile on the main stream, computed from weighted average runoff of the upper tributaries, agrees closely with the observed seasonal flow of the main stream. These statements all apply to the humid regions of the United States.

(12) Further studies are desirable to account for numerous great differences in average flow from adjacent tributaries within the same basin. There are ample data available. Consideration of runoff from melting snow is not included in the topics of this paper.

(13) Stream-flow is the sum of surface-runoff plus (and sometimes minus) ground-water supply or base-flow. Base-flow may be segregated from surface-runoff by the use of a ground-water depletion-curve in a manner apparently first suggested by Samuel Hall and D. Halton Thompson.

(14) The sub-factor of natural reservoir-detention or pondage (a drainage-basin characteristic) has a pronounced effect upon the rates of peak-flow and the distribution of intensities during the period of surface-runoff. Applications of the rational method, with the exception of the procedure of the Committee on Flood of the Boston Society of Civil Engineers, do not take cognizance of this element of pondage.

(15) Pondage, and all of the other sub-factors of the drainage-basin characteristics, can be best (and perhaps only) considered by the inclusion of a constant for the basin. This constant is reflected in a unit or characteristic hydrograph of runoff from the basin.

(16) In an analysis of the complex phenomena of the rainfall-runoff relations it is convenient to consider the three basic factors: (a) Rainfall intensity-duration; (b) drainage-basin characteristics--a constant for a given basin; and (c) infiltration or losses--a variable. The sub-factors may be grouped into each of these three basic factors.

(17) In the study of hydrology as a science, or in the application of hydrology to engineering design, the records of observed stream-flow are essential. Stream-flow recording-stations should be numerous and well distributed. The observations should be continuous. The value of stream-flow data, at any station, increases with the years of records. Intermittent records and records of less than ten years are of minor value.

(18) Theoretical and mathematical computation of runoff are valuable procedures in the investigation of the laws governing the relations between rainfall, losses, and runoff. This field of analysis has received but little attention in the United States. Studies in this line are very desirable. They will serve as important guides to research and experiment.

(19) Field and laboratory experiments with artificial rainfall are needed. Such experimentation should include:

(a) Observations of runoff hydrographs from long, narrow areas under various slopes and various surface-conditions such as impervious clay, sand, or loam, with and without vegetation. A series of such experiments will furnish basic data on the phenomena of surface-runoff including surface-velocity and time of concentration.

(b) Observation on these soils, for runoff and infiltration, under a series of artificial rains and drying-out periods. This will simulate the soil-moisture effect of intermittent rainfalls, and will furnish some data on the important but little-established relation between runoff and antecedent rainfalls. It is suggested that these, and similar experiments, be carried out in hydraulic laboratories and engineering experiment stations, or as thesis work by university students.

In this work the basic principles and findings of different hydrologists are noted together with referenced bibliography. The paper or review is unlike any heretofore presented. It is an endeavor to fulfill, in part, one of the primary objects of the American Geophysical Union--a clearing-house or coordinating agency for research in the geophysical sciences. The paper was prepared for presentation to the Lisbon meeting of the International Association of Hydrology. It will be of equal or greater interest to American hydrologists.

8 East Huron Street,
Chicago, Illinois

ON PHYSICS OF SOIL-MOISTURE

F. J. Veihmeyer, Chairman

The members of the Committee were asked to submit statements describing their field of soil-moisture investigations, the problems under investigation, and those contemplated in the immediate future. All of the members did not report. The following information is taken from the replies received.

O. W. Israelsen reports that at the Utah State Agricultural College they have, during recent years, studied the drainage of land overlying an artesian ground-water reservoir. Water-table depths have been studied in relation to the pumping of water from the artesian aquifer and flow from artesian wells. A non-technical progress-report of parts of the work has been published as a Station Bulletin. Final non-technical and technical reports are being prepared for publication as Station Bulletins. The research concerning the dynamics of water in soils has dealt primarily with water in saturated soils. Some of the work done recently in the Physics Laboratory of the Utah Station is briefly summarized as follows.

Use has been made of a photoelectric (photonic) cell from which to determine experimentally distribution-curves. Equipment for the control of capillary potential in pots has been developed, together with recording capillary potentiometers--a special form of differential potentiometer; and a flow-meter for seepage is being perfected. Some analyses of the problem of transportation of soluble salts in the seepage-water and the accumulation of alkali are being developed. A paper describing a method of computing the effective diameter of a well battery was published in Agricultural Engineering, February, 1933.

A field study of irrigation-water application efficiency as related to methods of application is contemplated. This study will include determinations of the moisture-content of soils before and after irrigation, and at appropriate periods between irrigations. It will include also an attempt to evaluate loss of water by deep percolation from irrigated soils in given time periods.

In the Bureau of Public Roads, United States Department of Agriculture, E. A. Willis states that soil-moisture investigations are carried on with the purpose of furnishing necessary or useful information for the design, construction, and maintenance of the public highway-system. Some of the more important specific problems in this field are: (1) Investigation of the capillary properties of soils in relation to heaving caused by freezing; (2) determination of the drainage-properties through investigation of the rate of capillary and gravitational flow of water through soils; (3) investigation of the permeability of soils in connection with the rate and amount of settlement of soils under loads; (4) determination of the load-supporting properties of soils at different moisture-contents; (5) investigation of the effect of various chemicals carried by ground-water on pavements and structures; (6) study of methods of improving the stability of soils; (7) development of apparatus and methods of test for revealing and measuring the fundamental properties of soils. Results of research are published principally in the Bureau's publication, "Public Roads," and in the Proceedings of the Highway Research Board, National Research Council.

Mr. Willis reports that other agencies carrying on work in this field are: (1) University of South Carolina; (2) Massachusetts Institute of Technology; (3) Engineering Experiment Station, Ohio State University; (4) Pennsylvania Highway Department; (5) Michigan Highway Department; and (6) Missouri Highway Department.

I. A. Dennison of the Bureau of Standards, United States Department of Commerce, reports that the soil-moisture investigations of that Bureau deal largely with the corrosion of metals buried in soils. One of the current projects is to correlate the moisture-content of the soils at various test-sites with the corrosiveness of the soils, as indicated by measurements of corrosion on specimens of various metals after certain periods of burial. An attempt is being made to correlate the moisture-equivalent of soils with their normal moisture-content. Considerable attention has been given to the influence of moisture on the corrosion of steel by soils in the laboratory, and it has been found that in the acid soils of the east, maximum corrosion occurs near the moisture-equivalent. At higher moisture-contents the rate of corrosion is reduced because of diminution in the oxygen-supply at the metal surface. Field and laboratory studies of the Bureau of Standards indicate that the permeability of soils to water and air is an important factor in their corrosiveness, and it appears that direct measurement of the permeability of soils and of those physical constants of soils which influence permeability such as structure, texture, degree of dispersion, etc., will be of considerable assistance in accounting for corrosion in soils. Dr. Dennison suggests that the Committee give detailed consideration to the subject of soil-permeability for the purpose of reaching agreement as to the most suitable method or methods for measuring this property directly, and to recommend the measurement of certain physical constants of soils as best characterizing permeability.

H. J. Fraser, formerly of the Department of Geology, Harvard University, has been engaged in experimental study of porosity and permeability of soils. The work has been completed and the results are now awaiting publication.

W. O. Smith's soil-moisture investigations with the Gulf Refining Company, Pittsburgh, Pennsylvania, have been mainly with capillary rise and transmission and retention of liquids in ideal soils. The results of these investigations have been published in Physical Review, Physics, Bulletin of the American Association of Petroleum Geologists, Journal of the American Chemical Society, and Industrial and Engineering Chemistry.

N. E. Edlefsen and F. J. Veihmeyer report the following activities in the field of soil-moisture investigations by the Division of Irrigation Investigations and Practice of the College of Agriculture, University of California. Some of the work is being carried on in cooperation with other divisions of the University. Vapor-pressure measurements of water in soils are being made. A method has been developed to measure the vapor-pressure over the full range of soil-moisture. This method has been found to be more rapid than any of the more or less standardized methods used heretofore. Some of the results and a description of the method will appear shortly in Soil Science and Review of Scientific Instruments. Measurements of soil-moisture have been made with a special electrical condenser which can be placed in soils both in laboratory samples and in the field. Results of these investigations will appear in Soil Science and Agricultural Engineering. Measurements of the potential of water in soils have been made with a special potentiometer using the dielectric method. Hysteresis studies on the potential of soil-moisture are also in progress. Field-studies on soil permeability for water are being carried on. The effect of texture and structure and the effect of change in structure brought on by soil-cultivation are being studied. Evaporation of water from water-logged soils is being observed in a series of tanks.

Studies are in progress on the availability of soil-moisture to plants, the effect of soil-moisture on transpiration, and the physiological responses of plants to varying soil-moisture conditions. Investigations of the development of roots of plants in relation to soil-moisture have been carried on. Studies extending over a period of seven years on the wilting of plants induced by moisture-deficiencies have just been completed. The factors affecting the water-holding capacity of soils and the movement of water in soils have been investigated. The forces with which water is held in soils have been studied by means of the freezing-point depression, dilatometer, seed-absorption, and vapor-pressure methods. Critical examinations have been made of some of the so-called soil-moisture constants or "single value" soil-properties in relation to the availability of water to plants. The results of these studies have appeared in the publications of the California Agricultural Experiment Station, Soil Science, Plant Physiology, the Proceedings of the American Society of Horticultural Science, and in the Proceedings of the International Society of Soil Science.

A study is being made of stream-line and turbulent flow through granular materials. While not strictly in the field of physics of soil-moisture, mention of an investigation now in progress of the effect of pumping for irrigation from the alluvial cone of Putah Creek, California, may be of interest. A study of the rates of draft on the underground supply is being made to determine the relation between the total area of irrigable land to the amount of water which can be safely withdrawn from the basin without undue diminution of the supply.

A compilation of references to the literature on soil-moisture was made by F. J. Veihmeyer in collaboration with Guy Erwin of the Division of Agricultural Engineering, Bureau of Public Roads, United States Department of Agriculture. This bibliography was mimeographed and distributed in 1929 by the Department. It is fairly complete as to articles published up to and including 1924. It is hoped that this may serve as a basis for extension and compilation of a complete annotated bibliography on the physics of soil-moisture. The cooperation of the members of the Committee will be solicited for this purpose during the coming year.

College of Agriculture,
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ON UNDERGROUND-WATER

David G. Thompson, Chairman

Activities of the Committee

The Committee on Underground Water is a little more than one year old. It has not set up any elaborate program, but has preferred to start out modestly to discover ways in which it can be helpful to the workers engaged in investigations of the diverse phases of ground-water hydrology covered by it. It has not been possible to hold any meetings of the Committee, and all work has been done by correspondence. This method of work obviously has its disadvantages, especially when, as under the present arrangement no funds are available for correspondence, clerical help, etc. In spite of these handicaps the Chairman is glad to report that the members of the Committee have responded without fail when called upon for help.

One of the most definite accomplishments of the Committee has related to the preparation of information in regard to sources of information available to the worker. At the request of the Chairman, A. Nelson Sayre has prepared a list of publications which regularly carry abstract or bibliographic sections which include articles on ground-water hydrology. He has also prepared a list of articles of special significance in the subject during the past year. These have been chosen from a long list of titles collected by the Division of Ground-Water of the United States Geological Survey for the Annotated Bibliography of Economic Geology. In accordance with a resolution passed by a group of members of the Section of Hydrology which met in Berkeley, California, in October, 1932, the Chairman has prepared a "List of organizations studying problems of ground-water hydrology." It is doubtless incomplete and the Chairman will be glad to have brought to his attention the names of any other organizations that should be included in the list. The three lists described in this paragraph are appended to this report (see Appendix A).

As indicated in the report of a year ago the Chairman of the Committee has undertaken the preparation of a paper on artesian waters in the United States to be transmitted to the International Association of Scientific Hydrology for its meeting at Lisbon in September, 1933. In connection with his official work for the United States Geological Survey and partly for reference in this paper for the International Section, the Chairman has obtained from the Departments of Health of the 48 states and territories or other sources data in regard to the number of public supply-systems using water from surface or underground sources, the population, and for some systems the consumption, served from the two types of source. He has also summarized certain data presented in recently published census reports to show the importance of ground-water as a source of water-supply for irrigation. Also for use in the report to the International Association, Professor Howard E. Simpson, State Water Geologist of North Dakota, has furnished a statement in regard to efforts to reduce waste of water from flowing wells in that State.

In the previous report of the Committee, mention was made of several suggested investigations that would be desirable. Most of these investigations obviously can be made only by individuals or organizations that may have funds and personnel available for such work. It is believed that the Committee performs its duty so far as these suggestions are concerned by bringing them to the attention of the workers who may have opportunity to make useful observations in regard to the subjects indicated, perhaps as incidental work in connection with other investigations.

Particular consideration has been given by the Committee to the suggestion of M. R. Lewis that there be made a study of the possibilities of legal control of the use of ground-water for irrigation. The need for legal control of the use of the ground-water resources of the country is recognized not only in connection with irrigation-projects, but also in connection with the development of water for public supplies and for industrial use; and in widely separated parts of the United States and the humid eastern states. Furthermore, in some areas the problem involves not merely the factor of quantity of water available, but also other factors relating to the quality of the water, as for example along sea-coasts and certain inland areas where there is danger of contamination of wells by salt-water, and in oil-fields where the relations between the ground-water and the oil-supplies must be considered. The factors involved in different areas are so interrelated that, in order to obtain satis-

factory results, the problem of legal control of ground-water supplies can not be considered from the standpoint of irrigation alone, but attention must at the same time be given to the problem in so far as it relates to the development of ground-waters for public supply and industrial use.

A question may be raised as to whether the consideration of the problem of legal control of ground-water is a proper function of a committee of the Section of Hydrology, the stated purpose of which relates primarily to the scientific phases and only incidentally to the practical phases of hydrology. In this connection, however, the fact should be recognized that such legal control of ground-water resources as now exists is largely founded on legal principles that were developed many years ago when much less was known about the conditions that influence the occurrence of ground-water. It seems that there may be some justification for the Committee on Underground Water to consider this problem, more particularly with a view to demonstrate first the desirability of legal control and second the possibility of making a practical application of scientific hydrologic principles to bring about an adequate control for the most efficient development of one of the country's valuable natural resources.

These considerations were communicated to the members of the Committee with a request for an expression of opinion as to whether further action should be taken. Most of those who commented on this matter favor some action, in part with qualifications as to the ground to be covered. However, action on the subject has been postponed until after the annual meeting of the Section.

The Chairman of the Committee also suggested to the members the desirability of a survey of educational facilities for students contemplating specializing in ground-water hydrology. This suggestion has been prompted by his experience in ground-water investigations in widely scattered parts of the country which has shown that in spite of the widespread development of ground-waters comparatively few engineers or geologists have sufficient knowledge of the principles involved to adequately interpret observational data that they may obtain in developing ground-water supplies. Apparently in only three or four schools are courses given in the subject, and there are few courses that cover certain important phases of the subject. The student in geology acquires little or no knowledge of the principles of hydrology involved in the development of ground-water supplies, and the engineering student obtains a very poor conception of the geologic conditions that govern the occurrence of ground-water and which, it is being realized more and more, must be given due attention in considering large-scale developments. Opinion in regard to the advisability of undertaking this proposal has been divided, with a slight majority in favor of proceeding further. Further consideration seems desirable, however, before any definite action is taken.

Review of current investigations

The limitations of time and space do not permit any extended review of current investigations. A statement of investigations in California, New Mexico, and Oregon by Arthur M. Piper is appended to this report. Brief statements furnished by several members of the Committee have been incorporated in the following pages of the report of the Chairman.

Attention may be called to a project recently begun providing for a quarterly compilation of "Current hydraulic laboratory research in the United States." This project was initiated jointly by the American Committee of the World Power Conference and the University of California. It provides for a central agency, the United States Bureau of Standards, which will "compile, publish, and distribute information relating to current research." Among the projects listed in the first quarterly report, dated April 1, 1933, the following will be of interest to ground-water hydrologists:

An investigation in the National Hydraulic Laboratory by R. B. Hunter and W. F. Stutz to study the characteristics of the so-called "deep-well" current-meters developed by the United States Geological Survey for explorations in deep wells, to calibrate the meters, and determine their reliability in detecting the locations and extent of leaks in casings.

An investigation by Charles H. Lee in the Pacific Hydrologic Laboratory, in San Francisco, on the relation of permeability of granular materials to particle-size;

and another investigation by Mr. Lee on the relation of head to flow of water through partially saturated materials.

An investigation at the Massachusetts Institute of Technology by Professor T. R. Camp and E. L. Bean, relating to the flow of water through filter-sands.

An investigation by O. E. Meinzer and V. C. Fishel in the hydrological laboratory of the United States Geological Survey which has as its purpose the determination of whether there is a flow of liquids through porous materials with a gradient as low as one foot per mile or less, and if there is, to ascertain whether it follows Darcy's law.

A field investigation by the United States Geological Survey in cooperation with the Conservation and Survey Department of the University of Nebraska, under the supervision of L. K. Wenzel to determine the practicability of using the so-called Thiem method of determining the permeability of water-bearing materials. This investigation was described in a brief paper by Mr. Wenzel presented at the 1932 meeting of the Section of Hydrology.

The Division of Ground Water of the United States Geological Survey is now, or during the past year, has been engaged on about 40 projects in 16 states and in almost every one of these some feature of special interest to hydrologists in addition to routine data has been studied. Some of the special features were mentioned in the report of a year ago and it is possible to mention here the most significant additional studies. A detailed list of the investigations in progress is contained in the annual report of the Director of the Geological Survey. All of the investigations are in cooperation with state or other governmental agencies.

One important development is the increasing use of water-level recorders to obtain continuous records of the fluctuations of water-levels in wells and extension of periodic measurements of the depth to water in numerous other observation-wells not equipped with recorders. There are now in use 116 recorders in 14 states. This is an increase of about 65 in two and a half years. About 1,100 wells are being measured regularly at intervals of a month or less, and about 1,500 wells are being measured more irregularly, but at least once or twice a year. In addition a considerable number of wells are being measured by governmental agencies other than those of the Federal Government, or by Private agencies, in other states, notably in New York, North Carolina, and California.

These records are yielding much useful information. In several localities observations have now covered long enough periods--from 5 to more than 30 years--to give considerable information not only on seasonal trends but also on secular swings of longer periods due to changes in precipitation, fluctuations in consumption of water, etc. In other areas, even though the records are of relative short duration, they have yielded information in regard to certain fundamental principles. For example, in Ogden Valley, Utah, in an investigation by R. M. Leggette, G. M. Taylor, and L. K. Wenzel, at each of two localities, recorders have been installed on three different wells, and at a third locality on two wells. The wells at each locality penetrate different water-bearing horizons, the uppermost tapping the water-table and the others tapping beds in which the water is under artesian pressure. The distribution of the wells is favorable for studies of the progress of recharge from one locality to another and of pressure-impulses in the artesian formations resulting from changes in the rate of withdrawal in a well-field, that of the City of Ogden, which has a normal capacity of about 10 million gallons a day.

Every opportunity has been taken to determine the applicability of Thiem's method of determining the permeability of water-bearing formations. The results of the application of the method in Portales Valley have been described by C. V. Theis in a recently published report in the Tenth Biennial Report of the State Engineer of New Mexico.

Studies by the Geological Survey and cooperating parties relating to the relation between fresh ground-water and salt-water have been made in several states, notably on Long Island, New York, New Jersey, North Carolina, Florida, and Texas. Exploratory work with a deep-well current-meter and electrical-resistance apparatus to determine

the source of salt-water and fresh water carried on by V. T. Stringfield and A. G. Fiedler in the vicinity of Sarasota, Florida, has proven enlightening particularly in showing that much of the water was coming from horizons that were supposed to contain very little water.

A new type of hydrologic study was undertaken during the past year by the Geological Survey in cooperation with the Michigan Department of Conservation to determine the availability of ground-water for fighting forest-fires. The projects provides for the determination, by numerous test-holes, of areas where ground-water occurs within a few feet of the surface and can be quickly obtained by sinking wells, and involves a consideration of seasonal fluctuations of the water-level, permeability of the sand, etc. The work is being carried on by G. I. Stewart and A. W. Bergquist for the State Department of Conservation and S. W. Lohman for the Geological Survey.

The study of several fundamental factors affecting the occurrence of ground-water is being continued in extensive investigations in Texas under the direction of Walter N. White. An investigation in which an attempt is being made to determine the reservoir-capacity of the Edwards limestone, which is the principal water-bearing formation in the San Antonio, Texas, area, was begun during the past year by A. N. Sayre and Penn P. Livingston.

In an investigation of ground-water conditions along the Kootenai River near the Canadian boundary in Idaho by T. R. Newell of the United States Geological Survey and L. T. Jessup of the United States Bureau of Agricultural Engineering, study has been made of the effects of the changing stages of the river on the position of the ground-water table.

Several studies pertaining to ground-water hydrology are being made by organizations or individuals other than governmental bureaus. Professor Gordon M. Fair and Lorenus P. Hatch of the School of Engineering of Harvard University have recently completed a paper on "The flow of water through sand." In this paper, which is based on three years' work, the authors develop a rational formulation of the laws of flow governing the passage of water through sand under conditions similar to those encountered in filter-beds, including the condition that occurs during the process of backwashing when the head is so great that the sand is expanded until it is suspended in the water. The formulae cover flow through both stratified and unstratified sands.

In connection with extended hearings on an application of the City of New York to the State Water Power and Control Commission for permission to develop a large quantity of ground-water on Long Island much work during the past year has been done in studying conditions on the western end of the Island, both by the City and by other interested municipalities and private water companies. Although much of the information collected has been of a more or less routine nature, consideration has been given to certain fundamental problems. Thomas H. Wiggin, Chief Engineer of the Federal Water Service Company has made an estimate of the percentage of available recharge-area in the thickly populated area of Brooklyn and Queens where the opportunity for recharge has been greatly reduced by the construction of buildings, sidewalks, and roads. A contour map of the water-table of the west end of the Island has been made under the joint auspices of the City of New York Department of Water Supply, Gas, and Electricity, the Federal Water Service Company, and the Jamaica Water Company. This map offers an excellent opportunity for a comparison with the very elaborate map of the water-table as it was in 1903 based on studies by Walter E. Spear for the New York Board of Water Supply.

The results of two studies at the Utah Agricultural Experiment Station relating to ground-water conditions as affecting land drainage has been published during the past year. One paper on "The theory of water-logging of agricultural land" (Proc. Utah Acad. Sci., v. 9, 1-6, 1932) by David Homer and Willard Gardner, considers conditions where water-logging of lands may result from lateral movement of water from canals in permeable beds overlain by less pervious beds. The other, by Orville L. Eliason and Dr. Gardner, is entitled "Computing the effective diameter of a well battery by means of Darcy's law" (Agri. Eng., v. 14, No. 2, 1933).

The brief descriptions above relate to problems primarily of interest to the hydrologist in his work of studying ground-water as a natural resource. Reports re-

ceived by the Chairman indicate that considerable attention is also being given to ground-water as a geological agent and as an element to watch carefully in the production of oil, gas, and other resources.

A. C. Swinnerton has contributed a valuable paper on the subject of formation of limestone caverns which will be of interest to hydrologists in regions where water occurs in solution openings in limestone (Origin of limestone caverns, Bull. Geol. Soc. Amer., v. 43, 663-694, 1932).

W. D. Johnston, Jr., reports that he has endeavored to collect information concerning the occurrence of water in mines. He states that descriptions of mining districts in desert countries usually give the depth to the water-table, whether the mines are wet or dry, and rarely some isolated pumpage figures, but unless former variations of the water-table enter into the consideration of the genesis of the ore deposits the treatment of mine-water geology is generally inadequate. An interested reader usually looks in vain for information as to the rate of penetration of rain-water, seasonal or other variations in pumpage rate, the behavior of faults or other channels for the descent of water, the variation in the chemical character of the water with depth or from one type of rock to another, and similar related questions. Dr. Johnston suggests that geologists engaged in the study of mining districts record more fully observations on the occurrence, quantity, and behavior of mine-waters and, whenever possible, give especial consideration to this important subject.

A. F. Melcher reports that oil-producing companies are giving considerable attention to underground waters as affecting the production of oil and gas. He has submitted the following statement in regard to this subject.

"The paper by Morris Muskat on Problems of underground water-flow in the oil industry, which was reported in the Transactions of the American Geophysical Union for 1932, gives a very good and general idea of some of the water-problems as related to the oil industry. Until recently in the Mid-Continent field the presence of water in an oil-sand was regarded as detrimental to the highest percentage-recovery of oil. During the last few years the operators are beginning to learn that the presence of water under pressure in an oil-sand may very appreciably increase the percentage-recovery of oil when the water is properly controlled and used to drive out the oil. In one field in Kansas where the pool is being operated almost altogether by one company, the natural water-flood is increasing the percentage-recovery of oil by more than 50 per cent of the recovery of oil that would be possible without this natural water-flood. Better data can be obtained on increase of percentage of recovery by the natural water-flood as the oil sand becomes more nearly watered out. Oil-sand cores have been taken in this pool for information on percentage-recovery with and without the natural water-flood as well as for the operation of the field and controlling the encroaching water-flood.

"The East Texas field has an edge-water on the west side of the field. The edge-water extends horizontally into the Woodbine sand underneath the oil for some distance to the eastward forming a bottom water in this area. The operators in this field have planned to develop and operate this field so that they may make use of the natural water-flood for increasing the percentage-recovery of oil. Several of the operators have had cores of the oil-sand taken and analyzed for porosity, permeability, saturation with oil, and for profiles of these physical characteristics down through the sand to show the variations in texture and permeability. This information is to be used to make estimates of recovery of oil with and without the natural water-flood and for operating the field and for controlling the natural water-flood.

"Probably the main problem in control of an encroaching water-front in an oil-sand is to maintain a uniform water-front, as far as possible in all parts of the sand. Some of the difficulties in maintaining a uniform water-front in the sand are natural conditions and the artificial conditions. The natural conditions are non-uniform sand characteristics and variations in saturation of the oil-sand. The artificial difficulties may be due to methods of development and operation as well as to methods of proration and lack of enforcement of proration regulations. The East Texas field has about all these difficulties enumerated, especially those due to proration. The water encroachment in the East Texas field has been very slow to the present time. The water is not advancing as rapidly as the oil is being taken out at present. The

pressure in the field will have to be lower before the water will come into the sand as rapidly as the oil is taken out. For a given production of the field, the pressure to which the field must be lowered for the water to flow into the oil-sand as rapidly as the oil is removed can be calculated from the permeability of the sand and the differential pressure between the oil-sand and water-sand."

Dr. Melcher expresses the opinion that the East Texas field offers a good opportunity for a very high recovery of oil by natural water-flood, if a good method of proration can be enforced.

He reports that he is collecting material for a paper on water-flooding, both natural and artificial, in the Mid-Continent area, but it will probably be a year or more before it is finished. He is studying cores from several pools or fields where natural flooding is taking place and one area where artificial flooding is in progress.

Morris Muskat reports that research on the underground flow of water as affecting the development of oil-fields has been continued in the laboratory of the Gulf Research and Development Corporation. He calls attention to the fact that the eastern division of the American Petroleum Institute Committee on Development and Production Research, under the chairmanship of K. B. Nowels, is considering the question of standardization methods of determining permeabilities and porosities, and the nomenclature used in connection with such work. Dr. Muskat also refers to three recent papers dealing with problems of ground-water encountered in the production of oil as follows: Stanley Gill, Application of water analysis to petroleum technology, Oil Weekly, v. 66, p. 30, July 11, 1932, and p. 24, July 18, 1932; K. B. Nowels, The mechanics of water-movement in natural and artificial flooding of oil-sands, Oil Weekly, v. 67, p. 29, October 3, 1932; and E. K. Soper, Limitations of ground-water as aid in determination of hidden geologic structure, Amer. Assoc. Pet. Geol. Bull., v. 16, p. 335, April, 1932.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--LIST OF ORGANIZATIONS STUDYING PROBLEMS OF GROUND-WATER HYDROLOGY[a]

Organization	Scope of work	Publications
	Federal agencies	
U. S. Geological Survey, Water Resources Branch, Divisions of Ground Water and Quality of Water, in cooperation with State and other governmental organizations[b]	General investigations of occurrence, quantity, head, and quality of ground-water as affected by geologic conditions, methods of recovery, development, and use of ground-water supplies; detailed investigations of safe yield of water-bearing formations and effects of pumping; maintains small hydrologic laboratory	Water-supply papers, mimeographed memoranda for the press, bulletins of the U.S. Geological Survey, and publications of cooperating State organizations.
U. S. Geological Survey, Geologic Branch, Section of Geology, Section of Fuels (in cooperation with American Petroleum Institute)	Ground-water problems bearing on the accumulation of petroleum	Bulletins, etc., of the U. S. Geological Survey
U. S. Geological Survey, Section of Geology of Metalliferous Deposits	Studies quantity and quality of ground-water in relation to problems of mineral deposits	Ditto
U. S. Bureau of Agricultural Engineering, and cooperating State agricultural experiment stations	Investigations relating to drainage and agricultural use of ground-water, especially irrigation	Publications of Department of Agriculture

Organization	Scope of work	Publications
	Federal agencies--Continued	
U. S. Bureau of Mines	Quality and quantity of mine-waters	Publications of Bureau of Mines
	State or local governmental agencies	
(Exclusive of work done in cooperation with U. S. Geological Survey; most State Geological Surveys and some State Engineers or State Departments of Health collect and file logs and other information in regard to water-wells.)		
Arizona Agricultural Experiment Station	Investigations of ground-water supplies, well-drilling, and pumping for irrigation	State bulletins
California Division of Water Rights	Investigations especially of quantity of water available for irrigation	Ditto
Illinois Department of Registration and Education, State Geological Survey Division	Collection of general information in regard to ground-water wells	Ditto
Illinois Department of Registration and Education, State Water Survey Division	Collection of information relating especially to public water-supplies of the State	Ditto
Iowa Geological Survey	Collection of well-logs and study deep-well samples	Ditto
Minnesota Geological Survey	General investigation in northwestern part of State	Ditto
Missouri Bureau of Geology and Mines	Collection of general information in regard to ground-water and wells	Ditto
Montana Bureau of Mines and Geology	General investigation in parts of State	State publications (mimeographed)
North Dakota Geological Survey, State Water Geologist	Collection of ground-water data, study of flowing wells in relation to conservation of artesian water	State bulletins
Utah Agricultural College	Collection of records of wells in different parts of State and studies in connection with drainage-problems	Ditto
Wisconsin Geological and Natural History Survey	Collection of general information in regard to ground-water	Ditto
	Societies and similar organizations[c]	
American Association of Water Well Drillers, Well-Log Committee[d]	Preparation of standard form of log for water-well drillers	Information published in several well-drillers magazines

Organization	Scope of work	Publications
Societies and similar organizations--Continued		
American Geophysical Union, Section of Hydrology, Committee on Underground Water	Activities relating to the stimulation of research, dissemination of literature, coordination of workers and correlation of results of all phases of ground-water hydrology	Transactions of American Geophysical Union (published by National Research Council)
American Petroleum Institute[e)]	Underground temperatures, quality and movement of water in relation to accumulation of petroleum	Bulletins of American Petroleum Institute and Texas Bureau of Economic Geology
American Petroleum Institute, Eastern Committee on Development and Production Research	Standardization of methods for determining porosities and permeabilities of sands, and of nomenclature relating thereto	Bulletins of American Petroleum Institute
American Public Health Association, Sub-committee on Ground-Water of the Committee on Water-Supply	Ground-water problems relating to sanitation and health, including pollution of ground-water supplies, chlorination, mottling of teeth resulting from certain types of water	
American Society of Civil Engineers, Irrigation Division, Committee on Conservation of Water		
American Society of Civil Engineers, Irrigation Division, Committee on Drainage of Irrigated Lands	Problems relating to drainage of lands by wells	Proceedings, American Society Civil Engineers
American Water Works Association, Committee on Ground-water Collection	Preparation of material for Manual of Water Works Practice	
American Water Works Association, Section of Abstracts	Preparation of abstracts relating to all phases of water-supply	Journal of the American Water Works Association
National Land Use Planning Committee, Technical Advisory Committee on Reclamation, Drainage, and Irrigation Policies	Consideration of legal control of use of ground-water for irrigation	
National Research Council, Division of Geology	Abstracts of literature relating to ground-water hydrology	Published semi-annually in "Annotated Bibliography of Economic Geology"
National Research Council, Division of Geology, Committee on Conservation of the Scientific Results of Drilling	Activities relating to collection of well-data, including preservation of well-cores and samples	Annual reports of Division of Geology, National Research Council

a) The phases of ground-water hydrology being studied by some of the organizations given in this list are closely related, in some cases mostly so, to the work of other committees of the Section of Hydrology, particularly of those on absorption and transpiration, physics of soil-moisture, and the chemistry of natural waters.

b) A large part of the ground-water work of the United States Geological Survey is done in cooperation with State Geological Surveys or other State, county, or municipal bureaus. According to the annual report of the Director of the Geological Survey for the fiscal year ending June 30, 1932, such work was carried on in cooperation with the following organizations: Arkansas Geological Survey; East Bay Municipal Utility District in California; Florida Geological Survey; Territory of Hawaii; Idaho Department of Reclamation; Nebraska State Conservation and Survey Division; New Jersey State Water Policy Commission; New Jersey Department of Conservation and Development; State Engineer of New Mexico; Joint Legislative Committee Investigating the Water Resources of the State of New York; Oregon State Agricultural Experiment Station; Pennsylvania Geological Survey; Tennessee Geological Survey; Texas State Board of Water Engineers; the City of Salt Lake City, Utah; and the Virginia Geological Survey. In the fiscal year ending June 30, 1933, in addition to most of these organizations, work is also being done in cooperation with the Arkansas Agricultural Experiment Station, Michigan State Department of Conservation, Nassau County (New York) Board of Supervisors, Suffolk County (New York) Board of Supervisors, North Carolina Department of Conservation and Development, and the City of Ogden, Utah. Some of these organizations do considerable independent work on ground-water problems.

c) In addition to the organizations listed, members of a number of other organizations, including American Physical Society, American Association of Petroleum Geologists, Geological Society of America, and Society of Economic Geologists, are engaged in the study of problems of ground-water hydrology, but these associations do not have definite committees working on these problems. A number of water-supply engineering firms and petroleum-producing companies also from time to time make fundamental studies of such problems.

d) The American Association of Water Well Drillers has associated with it ten State or other local associations of well drillers.

e) In part in cooperation with Texas Bureau of Economic Geology.

APPENDIX B--INVESTIGATIONS OF UNDERGROUND-WATER PROBLEMS IN CALIFORNIA, NEW MEXICO, AND OREGON

Arthur M. Piper

California

Investigations by the California Department of Public Works, Division of Water Resources (based on written communication from Harold Conkling, Deputy State Engineer)--The Division of Water Resources, California Department of Public Works, has in the past year conducted investigations of ground-water problems in the great central valley of the State (California Trough); in the Salinas and Santa Clara Valleys of the central part of the State; also in the South Coastal Basin and in Ventura County, in southern California. In these investigations the Bureau of Agricultural Engineering of the United States Department of Agriculture, the Geological Survey of the United States Department of the Interior, and many local agencies have cooperated. In large part, the activities of the past year are continuations of investigations summarized in an earlier statement (A. M. Piper, Investigations of underground-water problems in Arizona, California, New Mexico, and Oregon, National Research Council, Trans. Amer. Geophys. Union, 13th annual meeting, 308-309, 1932). Progress in 1932-33 is summarized in the following paragraphs.

The major field and office studies in the California Trough were completed prior to 1932 in connection with preliminary investigations of the comprehensive State Water Plan (Report to Legislature of 1931 on State water plan, California Dept. Pub. Works, Div. Water Resources, Bull. 25, 204 pp., 1930). The work which has been done since consists of new studies to assemble the information in a form adapted to the needs of

different Federal agencies which have been studying that plan. Some field work in this valley has been continued, however, by measurements of depth of water in wells, particularly in the southern part of the San Joaquin Valley.

The field work in the Salinas Valley was completed in 1933 and a short final report will be issued within the year. This investigation was undertaken to determine whether the draft on the underground water was exceeding the recharge, and to develop other hydrologic relations; it was intended as a basis for additional work if in the future it should be determined that it was necessary to conserve further the water now being wasted. No plan to modify the present utilization, however, is now proposed. The methods evolved in the South Coastal Basin for determining specific yield were used in Salinas Basin in spite of the fact that those methods have not yet been checked. It was felt, however, that it was necessary to approximate the quantity of water now remaining underground within commercial pumping-lifts in the Salinas Valley and that an estimate under these conditions was justified.

The field work in the Santa Clara Valley was completed early in 1933 and a report of the results will be issued within the year. This investigation was primarily to determine whether there existed a deficiency of water and whether there was sufficient water now wasted into the ocean during floods to overcome such deficiency. Ground-water conditions were investigated particularly, together with measurements of percolation. An opinion was drawn as to the proportionate specific yield in various subdivisions of the Valley but estimates of the magnitude of the specific yield were not made.

The work which has been done in the South Coastal Basin during the past year includes: (1) Collection of records of ground-water level; (2) collection of well-logs; (3) experimental work in both field and laboratory to determine the specific yield of the various types of sediment which compose the valley-fill; (4) computations based on the specific yield to determine the storage-capacities of the underground basins; (5) compilation of geologic data bearing on the ground-water problems; (6) study of the chemical character of the ground-water in cooperation with the United States Bureau of Plant Industry; (7) collection of climatologic records to analyze further the penetration of rainfall; (8) survey of utilization of land to determine the draft on the water-supply; (9) determination of non-economic uses of water in cooperation with the United States Geological Survey and the United States Department of Agriculture.

Several methods have been used to measure the porosity and specific retention of many samples of different types of alluvial material from the South Coastal Basin and it is hoped to work out general laws which can be used to estimate within reasonable limits the specific yield of a sediment without actually measuring its porosity and specific retention. The data have not yet been completely analyzed and it is not certain that such laws can be formulated. However, experimental work has progressed to the point that tentative estimates of the specific yield are now being applied to obtain the storage-capacities of the various basins. A report on the laboratory methods is now being written and it is hoped that a report on the entire project can be made some time during the year. A report is now being written by C. S. Scofield, Principal Agriculturist, Bureau of Plant Industry, on the results of determinations of the chemical character of the water.

A report giving recorded water-levels in each well throughout the Basin up to January 1, 1932, was published during 1932.

The necessary phases of this work will be continued provided funds are made available. The work is being done largely in cooperation with local agencies for the purpose of developing a plan for the most economical utilization and conservation of local and imported water-supplies.

Field work on the hydrologic phases of the Ventura County investigation was completed in the fall of 1932. During that year also, a geologic investigation of the sedimentary deposits was begun and completed to formulate plans for the best utilization of the underground reservoirs. The chemical character of the underground water and other factors necessary to a comprehensive plan have been investigated. At the present time an intensive study is being made of the utilization of surface-water through storage in reservoirs in conjunction with better utilization of the under-

ground reservoirs to develop an adequate water-supply within feasible financial limits. It is expected that a report on this investigation will be completed this year. To this investigation the experience of study in the South Coastal Basin has been applied.

Investigations by the United States Geological Survey--The study by H. C. Troxell of the source and disposal of water in the channel of the lower Santa Ana River (A. M. Piper, op. cit., p. 309) has been continued, with particular attention to the consumption of water by vegetation adjacent to the river. It is contemplated that field work will be continued another year before a report is prepared. This study is one phase of the investigation of non-economic uses of water in the South Coastal Basin being made by the Department of Public Works.

The cooperative investigation of ground-water conditions in the Mokelumne Region, central California (A. M. Piper, Idem), has been continued without material change in its immediate objectives. A more effective technique in estimating the penetration of rainfall and the consumptive use of water by vineyards and orchards is believed to have been developed, chiefly by working with cultivated fields as units rather than with experimental plats of restricted area. Experiments with an approximate method of determining the specific yield of water-bearing materials seem promising but a final technique has not been formulated. Attention to the niceties of stream-gaging technique coupled with frequent measurements of the stream-flow has improved materially the determination of seepage-losses from the Mokelumne River. Previous work has shown that although the River flows for a considerable distance across the alluvial plain of the California Trough the losses by downward percolation are relatively small and but little larger than the uncertainty in routine methods of stream-gaging. The intensive study of the geology of the region, begun in 1931, has been completed and a preliminary report prepared (H. S. Gale, A. M. Piper, and H. E. Thomas, The geology of the Mokelumne River basin, California, U. S. Geol. Survey, typewritten rep., 377 pp., released Dec. 23, 1932).

Investigations by the Bureau of Agricultural Engineering--The Bureau of Agricultural Engineering, United States Department of Agriculture, in cooperation with State and other agencies, has made intensive studies in southern California of rainfall-penetration and consumptive use of water on the valley plains, also of the storage of water underground by spreading excess surface-water on the alluvial fans. The scope of these studies places them in the field of other committees of the Section of Hydrology; accordingly, they are not summarized here.

The Bureau of Agricultural Engineering is also studying the utilization of ground-water for irrigation (statement based on excerpts from the Annual Report of the Chief, Bureau of Agricultural Engineering, to the Secretary, United States Department of Agriculture, for the year ending June 30, 1932) by pumping from wells; this is under the direction of Carl Rohwer, Associate Irrigation Engineer, and comprises field-projects in California and four other western states. In this study an effort is being made to secure greater efficiency in utilization by (1) ascertaining the best methods of constructing wells under various conditions, and (2) selecting the type of pump best suited to the specific conditions. The practical usefulness of this study is evidenced by the striking recent increase in the use of pumped water for irrigation, not only to supplement gravity-water supplies in times of shortage but also to replace gravity-supplies or, in some new projects, to be chosen in preference. In the 1920-30 census decade the area irrigated wholly or partly from pumps nearly doubled, although the total irrigated area did not increase correspondingly; almost one-third of the total irrigated area is now served by pumps. In the same period the capital investment of enterprises using pumped water tripled and became more than half the total investment of all irrigation enterprises.

Investigations by other agencies--Less comprehensive investigations are in progress by other agencies in California. Measurements of depth to water in observation-wells and determination of fluctuations in the water-table are made by the Water Departments of the cities of Los Angeles and Pasadena and by numerous flood-control and water-utilization districts, especially in the southern part of the State.

S. T. Harding in a written communication reports an interesting hydrologic effect of the current depressed economic conditions. In the district about Yuba City, in

north-central California, the draft on the ground-water for irrigation decreased about 30 per cent in 1932, owing chiefly to the low value of crops. As a result the water-table has risen during the winter of 1932-33, whereas little or no recovery would have been anticipated had the draft been normal.

New Mexico

The United States Geological Survey, in cooperation with the State Engineer of New Mexico, has continued investigations of ground-water conditions in Curry, Roosevelt, and Lea counties, and in the Roswell artesian-basin, all in the southeastern part of the State. These seek to determine the safe yield of the respective basins with respect to recovery of the ground-water for beneficial use. Reports of progress in these investigations in the past year have been published in the biennial report of the State Engineer (C. V. Theis, Ground-water in Curry and Roosevelt counties, New Mexico: New Mexico, State Eng., Tenth Biennial Rep. 1930-1932, pp. 98-160, 1932; A. G. Fiedler and S. S. Nye, Progress-report of the Roswell artesian-basin investigation, pp. 162-182; S. S. Nye, Progress-report on the ground-water supply of northern Lea County, New Mexico, pp. 229-251).

Oregon

In the summary of a year ago (A. M. Piper, op. cit., p. 310), two projects in Oregon were mentioned as being conducted in cooperation between the United States Geological Survey and the Oregon Agricultural Experiment Station. Of these, the project at The Dalles has been completed and a report published (A. M. Piper, Geology and ground-water resources of the Dalles region, Oregon, U. S. Geol. Survey, Water-Supply Paper 659-B, pp. 107-189, 1932). In the second area under investigation--the Harney Basin in the southeastern part of the State--the geologic and hydrologic field-studies have been completed and a report is now in preparation. No new projects have been undertaken, but one is contemplated in the Milton-Freewater District in the northeastern part of the State adjacent to the Walla Walla District of southeastern Washington. The proposed investigation there involves some general phases of a program to utilize more efficiently the surface- and ground-water resources in the basin of the Walla Walla River, a tributary of the Columbia River.

U. S. Geological Survey,
Lodi, California

APPENDIX C--A SELECTED LIST OF PAPERS RELATING TO GROUND-WATER HYDROLOGY

A. N. Sayre

Eliason, Orville L., and Willard Gardner, Computing the effective diameter of a well battery by means of Darcy's Law, Agric. Eng., v. 14, No. 2 (1933).

Homer, David, and Willard Gardner, The theory of water-logging of agricultural land, Utah Acad. Sci., v. 9, 1-6 (1932).

Leggette, R. M., and G. H. Taylor, Ground-water supplies in the vicinity of Salt Lake City, Utah (cooperative report by Salt Lake City and U. S. Geol. Survey), U. S. Dept. Interior P. N. 64395, 9 pp. (mimeographed), maps, July 23, 1932.

Leitch, R. D., and others, Character of drainage from mines in the Thick Freeport coal-bed, Pennsylvania, U. S. Bur. Mines, Rep. Investigation 3193, 29 pp. (mimeographed), Nov. 1932.

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Foreign publications--Geologische Zentralblatt; Institute of Civil Engineers; Neues Jahrbuch; Revue de Geologie; and Water and Water Engineering.

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ON DYNAMICS OF STREAMS

Lorenz G. Straub, Chairman

During the past year, which is the first of the Committee's existence, primary consideration has been given to following up a number of proposals which originated largely at a meeting of several members of the Committee in Washington on the occasion of the thirteenth annual meeting of the American Geophysical Union. For the most part, the work has centered about assembling information which might eventually assist in correlating and thereby accelerating the research conducted by various agencies interested in the dynamics of streams.

Briefly, the following basic activities have been given attention: (a) A tentative list has been assembled of societies, committees, and other organizations whose functions and activities overlap those of this Committee; (b) in view of the important place relative to the Committee's work held by hydraulic laboratories equipped for experimental work on open-channel flow-phenomena, sedimentation, erosion, etc., a separate list [from (a)] was prepared of these institutions; (c) a third list, supplementing the aforementioned, was compiled of individuals of note who are engaged in work which is of interest to the Committee; (d) steps have been taken toward compiling a bibliography of outstanding papers in all languages dealing with scientific investigations on the dynamics of streams; and (e) the Committee has fostered the preparation of eight of the papers presented at this year's annual meeting of the Section of Hydrology.

The names of organizations and individuals added to the Committee's register are intended to include both foreign and American names, in the hope of eventually encouraging a more rapid dissemination of the results of pertinent research-work.

Current and recent investigations on the action of water in surface-flow and flow in natural channels

Space does not permit giving detailed information concerning even a few of the eminent works in the field of the Committee's activities; the subject-matter is too broad. Suffice it here merely to mention some of the important developments, although doubtless many of equal importance will be inadvertently overlooked.

Laboratory studies--Possibly the most fruitful development of recent years in river-hydraulics research has been the application of laboratory methods to the study of flow-conditions in natural water-courses. It is true that these methods are not essentially new, but their value has not been generally appreciated until quite recently. A very few years ago hardly a laboratory in the country was equipped for the study of flow-conditions by means of miniature models of parts of natural water-courses. At present the analysis of river-structures by laboratory methods is one of the most mooted subjects of hydraulics. Only a few of the many projects [(1)--numbers are to references at close of paper] will be mentioned at this time.

The United States Waterways Experiment Station, which was established in 1930, has numerous river-hydraulics investigations in progress or recently completed. These include sediment investigations on the Mississippi River and tributaries, studies of the Bonnet Carre flood-way, studies of river cut-offs, backwater-effects, erosive force for various types of sediment, and bed-load diversion. The National Hydraulic Laboratory in Washington, the construction of which was completed only last year, is preparing to make fundamental river-hydraulics investigations. The United States Bureau of Reclamation is making experimental studies on models to assist with the design of its reclamation-projects. Within the last few years the University of California Laboratory has done much experimental work on open-channel flow-phenomena, including such studies as stream-line and turbulent flow through granular materials, the transportation of bed-load by streams, studies of the scale-effect on models, investigations of motion of salt-water through fresh water. The Massachusetts Institute of Technology has now a River-Hydraulics Laboratory devoted to investigations of such projects as wave-phenomena in channels, transportation of sand by running water, experimental study of sea-wall design, lateral spillway channels. At the University of Minnesota experimental projects include sediment transportation by running water, studies of the critical transporting-velocity for various types of granular material, seepage-velocities in earth- and sand-dams, etc. The University of Iowa has numerous research-projects under way dealing with the experimental design of river-hydraulic structures.

Other similar river dynamic experimental research-work is in progress at other laboratories in this country and in numerous foreign institutions (28). At a few of the latter the laboratory methods of river-hydraulic investigations have been in use for over two decades.

Soil erosion--Much valuable work in the study of soil-erosion conditions in the United States has been accomplished by the United States Bureau of Chemistry and Soils (2,3). The United States Department of Agriculture, cooperating with the States, is primarily concerned with studies relating to (a) the dynamics of erosional water (and wind) as pertaining to soil-transportation (in the solid and liquid states) and deposition; (b) the effect of these activities on the producing capacities of land; and (c) methods for slowing down runoff and erosion on agricultural lands of the Nation. The principal ultimate aim of this program is to reduce as much as possible the damaging effects of erosion to land, such as is caused (a) by direct removal of the more productive upper layers of soil and (b) by deposition of overwash and harmful erosional debris upon lowlands. Collateral benefits would be, a lessening of the choking of streams and of the filling of reservoirs, canals, ditches, culverts, and harbors through excessive sedimentation; prevention of the blocking of highways with erosional debris and better protection of watersheds.

Experimental studies on small plots of ground have been conducted recently by the Missouri Agricultural Experiment Station (4), also at the Texas Agricultural Experiment Station (5), in the State of Kansas (6), in Oklahoma (7), and elsewhere. By the time of the next annual meeting it is hoped to present considerable discussion on this subject.

Relations between streams and the channels they occupy--Much information concerning the hydraulic characteristics of rivers is being gathered by the Water Resources Branch of the Geological Survey. Pertinent information is published in the Water-Supply Papers of the Survey, also in the Water-Supply Papers of the various States with which the United States Geological Survey cooperates. A considerable amount of investigational work is conducted for the Federal Power Commission in connection with power-projects and applications and also for the State Department and the Internation-

al Joint Commission in connection with various water-problems along the International boundary between Canada and the United States.

One of the important phases of the work of the Survey is stream-gaging, and this part of its work, of course, is very largely built up upon and around the accumulation of experience concerning certain aspects of the relation between streams and the channels they occupy. More than 200 engineers engaged in this work and operating from 34 district offices afford a notable store of information and experience and also an instrumentality for a wide observation of such phenomena.

The Corps of Engineers, being in charge of the river- and harbor-work of this country, conducts numerous investigations concerning the regimen of rivers. Many valuable data have been published in the reports of the Mississippi River Commission, Missouri River Commission, professional papers of the Corps of Engineers, and in the reports of the Chief of Engineers. Still other pertinent information is given in the reports of the United States Coast and Geodetic Survey and House and Senate reports of Congress. Since the time of the Mississippi River flood of 1927, much activity has centered about gathering information concerning the rivers of America pursuant to the authorization and requirements given by House Document 308 of the 69th Session of Congress, 1st Session. The reports of this work are now being published.

The International Boundary Commission of the United States and Mexico has compiled considerable data and based thereon has proposed improvements for the development of the Rio Grande River (8).

Transportation of bed-load by running water--One of the most baffling problems in river hydraulics is the investigation of bed-load. Various theories have been set forth from time to time and methods have been proposed for correlating the results of laboratory-studies and field-investigations. P. du Boys (9) proposed a general formula based upon theoretical considerations which though frequently criticized still stands as one of the most important contributions to the subject. The most outstanding American contribution consists of careful observations made by G. K. Gilbert (10) in an artificial channel. Recent studies of G. K. Gilbert's data (11) indicate them to be specially consistent and in agreement with theoretical considerations. More detailed study of his investigations is now in progress. Other investigations of note have been made by F. Kreuter (12), F. Schaffernak (13), A. Schoklitsch (14), and others.

Although for many years there was comparatively little scientific study of the subject of transportation of bed-sediment by running water in recent years, stimulated by the possibilities of laboratory-research, much activity has developed in this field within the last two or three years. Research is now in progress at the United States Waterways Laboratory, the University of California, Massachusetts Institute of Technology, the University of Iowa, and at the University of Minnesota. Other hydraulics laboratories are considering beginning projects of this nature. Experimental studies have been made at Berlin (15,16) with a particular view of applying the results to river-models involving the analysis of erosion and deposition of sediment in natural streams.

Direct measurement of the bed-load of rivers has not been generally successful because in most cases the obstruction to flow caused by the trap has caused localized turbulence interfering with the gathering of representative quantities of material. Some of the most recent investigations, however, merit special consideration because of the care exercised in the design and operation of the apparatus (17,18).

Because of the long period of record available, more data have been compiled on European rivers than on American rivers concerning the effect of river improvements upon the river-profile and characteristics of bed-movement. Kupferschmid (23) has made a careful analysis of the changes in the bed of the Upper Rhine River, illustrating the movement of bars concurrently downstream. Studies have also been made of the amount of material transported by analyzing the changes in elevation of the stream-bed (24, 25).

In the literature on this field of research many contradictory statements may be found. Hence there is room for carefully planned studies both in the field and laboratory.

Scour below spillways--The erosion below spillways apparently is little influenced by the size of sediment particles forming the stream bed (26, 27) although the time required for the erosion to take place is considerably influenced by the size of the particles. There is, of course, some difference in the amount of erosion where the variation in size of bed-sediment particles is large. Studies of the resistance of particles to transportation indicates that they vary (26) according to the relation (S - 1) L, where S is the specific gravity of the material and L the linear dimension.

Suspended load of rivers--The direct measurement of the solid material carried in suspension by a river is far less subject to error than the measurement of the bed-load. Field-data are available therefore for many rivers. Some of these have been compiled (19,20) into monographs; others are still scattered through various articles. Measurements of the United States Geological Survey (21) and of the United States Department of Agriculture (22) on the Colorado River have been published; extensive investigations of the last few years made under the Corps of Engineers on the Missouri River system are still to be published.

Limited studies of the character of the material transported in suspension, especially with regard to its mechanical composition, indicate that essential information concerning the suspended-load transporting capacity of rivers may be obtained by taking this factor into consideration (11).

Nomenclature--With the rapid development of scientific studies in river hydraulics there is an evident lack of terminology. Thus far, for the most part, the terms used have been largely provincial, varying in different parts of the country. Other terms have been borrowed from foreign languages. Particular attention therefore will be given by the Committee to making up a tentative annotated nomenclature.

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APPENDIX A--HYDRAULICS LABORATORIES WITH FACILITIES FOR RESEARCH IN OPEN-CHANNEL FLOW AND RIVER HYDRAULICS

No.	Name of Institute	Address	Name of director (and principal associates)
1	The Experiment Institute for Hydraulic Engineering of the Technical University of Danzig	Free City of Danzig	F. W. O. Schulze R. Winkel C. Keutner
2	Hydraulics Laboratory of the Technical University of Berlin	Berlin, Germany	A. Ludin A. Agatz
3	Hydraulics Laboratory of the Technical University of Dresden	Dresden, Germany	H. Heiser O. Kirschmer
4	Hydraulics Laboratory of the Technical University of Munich	Munich, Germany	D. Thoma K. Dantscher
5	Forschungsinstitut für Wasserbau und Wasserkraft	Munich 2 N.W., Loristr. 2, Germany	(H. Engels, Prof. Emeritus) B. Esterer
6	River Hydraulics Laboratory of the Technical University of Karlsruhe	Karlsruhe, Germany	Th. Rehbock P. Böss
7	Hydraulics Laboratory of the Technical University of Darmstadt	Darmstadt, Germany	K. Thürnau
8	Preussische Versuchsanstalt für Wasserbau und Schiffbau	Berlin N.W. 87, Germany	R. Seifert B. Körner F. Eisner
9	Hydraulics Laboratory of the Technical University of Brunswick	Brunswick, Germany	(M. Möller, Prof. Emeritus) L. Leichtweis
10	The Experiment Institute for Hydraulics and Foundations at the Technical University of Hanover	Hanover, Germany	O. Franzius
11	Wasserbauversuchsanstalt der Marinewerft	Wilhelmshaven, Germany	W. Krüger

APPENDIX A--Continued

No.	Name of Institute	Address	Name of director (and principal associates)
12	Hydraulics Lab. of the Technical Univ. of Trondheim, Norway	Trondheim, Norway	O. Heggstad
13	River Hydraulics Laboratory of Holland	Delft, Holland	J. Th. Thijsse
14	Hydraulics Laboratory of Leningrad	Ligororka 44, log. 600, Leningrad, U.S.S.R.	V. E. Timonoff
15	The Experimental Laboratory for Hydraulics at the Federal Institute of Technology	Zurich, Switzerland	E. Meyer-Peter
16	The Hydraulics Laboratory of the Royal Engineering School of Padua	Padua, Italy	E. Scimemi
17	Kaiser Wilhelms-Institut für Strömungsforschung	Göttingen, Germany	L. Prandtl
18	The Hydraulics Structures Laboratory of the Royal Technical University of Stockholm	Stockholm, Sweden	W. K. A. Fellenius E. J. W. Lindquist
19	Hydraulics Laboratory of Bohemian Technical Univ. of Brünn	Brünn, Czechoslovakia	Antonin Smrcek
20	Hydraulics Laboratory of Victoria University	Manchester, England	A. H. Gibson
21	Hydraulics Laboratory of German Technical Univ. of Brünn	Brünn, Czechoslovakia	A. Schoklitsch
22	Hydraulics Laboratory of Bohemian Tech. Univ. of Prague	Prague, Czechoslovakia	B. Tolman
23	Laboratoire d'Hydraulique de l'Université de Toulouse	Toulouse, l'Université, /Haute-Garonne/ France	C. Camichel
24	The Experiment Institute for Hydraulic Engineering in Vienna	Ministerium für Land - und Forstwirtschaft, IX. Bz, Severingasse 7, Vienna, Austria	R. Ehrenberger
25	Hydraulics Laboratory of Royal School of Engineering of Milan	Milan, Italy	J. de Marchi
26	Hydraulic Structures Laboratory of the Royal Joseph Technical University of Budapest	Budapest, Hungary	A. Rohringer
27	L'Institut National de Recherches Hydrauliques et Hydrotechniques	Prague, Czechoslovakia	J. Smetana
28	National Hydraulic Laboratory, Bureau of Standards	Washington, D. C.	H. N. Eaton K. Hilding Beij C. A. Wright G. H. Keulegan
29	Alden Hydraulic Laboratory	Worcester Polytechnical Institute, Worcester, Massachusetts	C. M. Allen
30	Hydraulics Laboratory of the University of Toronto	Toronto, Canada	R. W. Angus
31	Hydraulics Laboratory of the University of Michigan	Ann Arbor, Michigan	H. W. King
32	River Hydraulics Laboratory of Mass. Institute of Technology	Cambridge, Massachusetts	K. C. Reynolds
33	Hydraulics Laboratory of the University of California	Berkeley, California	M. P. O'Brien
34	Colorado Experiment Station	Fort Collins, Colorado	Ralph L. Parshall
35	Iowa Hydraulic Institute	Iowa City, Iowa	Floyd A. Nagler D. L. Yarnell Martin Nelson

APPENDIX A--Continued

No.	Name of Institute	Address	Name of director (and principal associates)
36	Hydraulics Laboratory of the University of Illinois	Urbana, Illinois	M. L. Enger
37	Hydraulics Laboratory of the University of Minnesota	Minneapolis, Minnesota	Lorenz G. Straub
38	U. S. Waterways Experiment Station	Vicksburg, Mississippi	Herbert D. Vogel

APPENDIX B--LIST OF ORGANIZATIONS (NOT INCLUDING EXPERIMENT STATIONS) WHOSE WORK IS RELATED TO THAT OF THE COMMITTEE ON DYNAMICS OF STREAMS

No.	Name of organization	Address	Name of one or more members
1	Research Committee on Irrigation Hydraulics of the American Society of Civil Engineers	33 West 39th Street, New York, N.Y.	D. C. Henny, Chairman B. A. Etcheverry George W. Hawley Julian Hinds Ivan E. Houk M. P. O'Brien R. L. Parshall J. L. Savage Fred C. Scobey I. C. Steele J. C. Stevens Franklin Thomas
2	Hydraulic Division of the American Society of Mechanical Engineers	29 West 39th Street, New York, N.Y.	B. R. Van Leer, Chairman C. F. Merriam, Sec'y
3	U. S. Bureau of Reclamation	Denver, Colorado	Ivan E. Houk I. C. Steele E. W. Lane
4	Waterways Division of the American Society of Civil Engineers	33 West 39th Street, New York, N.Y.	J. C. Gotwals, Chairman W. H. McAlpine, Sec'y Geo. F. Nicholson C. M. Spofford Charles W. Kutz L. C. Sabin
5	International Boundary Commission of U.S. and Mexico	El Paso, Texas	L. M. Lawson
6	Bureau of Agricultural Engineering, U.S. Dept. of Agriculture	Washington, D. C.	S. H. McCrory
7	Committee on Sedimentation of the National Research Council	Washington, D. C.	H. H. Bennett
8	Committee on Chemistry of Natural Waters, American Geophysical Union	Washington, D. C.	C. S. Scofield, Chairman
9	Mississippi River Commission	Vicksburg, Miss.	Col. Ferguson, Pres. G. H. Matthes, Hydraulic Engineer
10	U.S. Geological Survey, Water Resources Branch	Washington, D. C.	N. C. Grover, Chief
11	Federal Power Commission	Washington, D. C.	Geo. Otis Smith, Chrm.
12	U. S. Corps of Engineers	War Department, Washington, D. C.	Lytle Brown, Major Gen., Chief of Engineers
13	International Joint Commission of the U.S. and Canada		

APPENDIX B--Continued

No.	Name of organization	Address	Name of one or more members
14	Bureau of Chemistry and Soils	U.S. Department of Agriculture, Washington, D. C.	H. H. Bennett, in charge of soil-erosion and moisture-conservation investigations
15	Ministry of Water Works	The Hague, Holland	J. Th. Thijsse
16	Reichsverkerministerium	Berlin, Germany	
17	Bundesministerium für Land und Forstwirtschaft	Vienna, Austria	
18	Badische Wasser- und Strassenbaudirektion	Karlsruhe, Germany	Oberregierungsbaurat Spiess
19	Génie Maritime	29 Avenue, Felix Faure, Paris	Barrillon, Ingenieur en Chef
20	La Commission Internationale des Grands Barrages de la Conférence Mondiale de l'Energie	7 Rue Magellan, Paris	A. Genthial, Secretary General
21	La Société hydrotechnique de France	116 Avenue d'Orléans, Paris 14e	J. Laurent, Ing. en Chef
22	L'Association Internationale Permanente des Congres de Navigation	Brussels, 38 Rue de Lovain, Belgium	J. Millecam, Secretary General
23	Des eidg. Amtes für Wasserwirtschaft, Eidg. Dept. des Innern	Berne, Switzerland	C. Mutzner
24	Texas Agricultural Experiment Station	College Station, Texas	D. Scoates
25	University of Missouri, Agricultural Experiment Station	Columbia, Missouri	W. H. Baker

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APPENDIX C--Continued

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ON CHEMISTRY OF NATURAL WATERS

Carl S. Scofield, Chairman

In the report from this Committee for 1932 there was a list of seven phases of the subject of Chemistry of Natural Waters to which the members of the Committee were giving attention. The present report gives a summary of the views and aims of the Committee members in respect to these phases and of some of the sources of information concerning them.

(1) The chemical composition of subsurface-waters in relation to geological environment and to such geological processes as ore-deposition and the accumulation of petroleum deposits

It is felt that in respect to this subject there is need for: (1) The assembly for publication, together with a critical digest and review, of all available data of the chemical analysis of the percolating waters contiguous to or related to ore-bodies and petroleum-deposits; (2) the collection and chemical analysis of a large number of additional samples of such waters. It is emphasized that the work of collecting these samples should be done under careful and competent supervision, taking into account rock-structure, the relation of the samples to such features as "fans" and "funnels" of porous material coinciding with ore-mineralization, the distinction between samples from atmospheric and juvenile sources, and the identification of waters residual from the deposition of ore-minerals and of those from surface-sources present because of the porosity of mineralized ground. The analyses should include the determination of as many constituents as possible, with special emphasis on the bases, including both ferrous and ferric iron, and boron and fluorine. In connection with these analyses, and their interpretation, consideration should be given to stream waters from metalliferous areas and the computation of their burdens of dissolved constituents.

In connection with this subject, it is reported that in Texas the Department of Petroleum Engineering, in cooperation with the Bureau of Economic Geology of the University, has been making a study of the underground waters and temperatures in relation to serpentine volcanic plugs in the vicinity of Austin, Texas. The study has been directed to ascertain the relationship of the chemistry of the waters to the serpentine, to the source of the waters, and to their method of migration into the serpentine reservoirs.

In this State also there has been completed recently a study of the underground waters of the Woodbine sand of east Texas, published as University of Texas Bulletin No. 3138, and a study of the underground waters of the Red River Valley district of northern Texas and southern Oklahoma. The report of this latter study has been prepared by Virgil E. Barnes and F. B. Plummer but is not yet published.

(2) The composition of subsurface-waters in relation to the corrosion of ferrous and concrete structures

Investigations on this subject are conducted by the United States Bureau of Standards at Washington. The findings to date are here summarized:

Corrosion of ferrous metals by soils is influenced largely by the presence of dissolved materials in the soil-water which may accelerate or diminish the rate of corrosion. Of these materials dissolved oxygen is obviously important, the occurrence of local corroded areas on metals being probably due largely to electrical currents set up between areas differing in oxygen-concentration. Corrosion, however, has been observed to occur in soils under certain conditions in the absence of oxygen. In general, the most severe corrosion occurs in soils in which the concentration of soluble material is high, and methods depending upon the concentration of soluble salts, such as determination of the electrical resistivity of soils, have been successfully employed to indicate areas of corrosive soils. Since the quantity of moisture in soils influences their corrosiveness, it is, of course, desirable to take into account this factor in interpreting measurements of soil-resistivity.

The concentration of hydrogen-ions in soils is, as would be expected, an important factor in their corrosiveness, the rate of corrosion increasing with decrease in the

sustained pH value of the soil. It appears, however, from our studies that the total acidity of a soil is a more exact measure of corrosion than its pH value. The influence of the total acidity of soils in corrosion has been attributed to its tendency to inhibit the formation of films of corrosion-products which otherwise would tend to protect against further corrosion.

Certain materials occurring naturally in soil-waters appear to inhibit corrosion. Thus carbonates and bicarbonates of calcium and magnesium present in soil-waters may, under certain conditions of concentration and reaction, form a thin film or membrane on the surface of the metal which tends to protect the metal against further corrosion. This principle has been utilized successfully in the treatment of water with lime to reduce its corrosive action on the interior of water-pipes.

References to the general subject of soil-corrosion will be found in Letter Circulars 328 and 329, issued by the Bureau of Standards.

(3) The occurrence of radioactive and rare elements in spring-waters and their geological interpretation

Inquiry in this field runs along two lines: The radioactive constituents of waters in relation to medicinal uses, and the radioactivity of certain spring-waters and of the precipitated deposits from them in relation to the age of the deposits. No active work on either of these lines has been reported to the Committee during the current year.

(4) The composition of water in relation to the processes of base exchange in geological structure and in soils

The following paragraphs indicate the trend of thought in this field as formulated by two of the men, W. P. Kelley and L. C. Case, who are actively engaged in it:

Since many natural waters contain substantial amounts of dissolved salts, both soils and clay-deposits are often subjected to the action of these solutions in the state of nature. Under certain conditions more or less base-exchange takes place between the clay-minerals and these percolating solutions. Investigation has abundantly proven that many natural clays and soils are readily acted upon by dilute salt-solutions of a composition similar to that of many natural waters. This reaction is commonly referred to as base-exchange. The extent to which the clay-minerals undergo base-exchange depends chiefly upon the composition and the concentration of the percolating solutions. The replaceable base of natural clays that have not been in contact with salt-solutions is ordinarily chiefly calcium. When a dilute solution of sodium chloride is percolated through such a clay, more or less of its calcium will be replaced by sodium. Magnesium salts are also capable of producing the same type of base-exchange. In fact, magnesium is more active in its base-replacing power than is sodium. It follows then, that a determination of the replaceable bases in a given clay-deposit may afford evidence as to its geological history, particularly as to the nature of the salt-solutions which have percolated through it.

Investigations conducted with primary reference to the use of saline irrigation-water have led to a study of the action of the effects of various types of water. A wide range of solutions has been used in this study, including normal sea-water from the Pacific Ocean. The results have demonstrated that a clay-deposit which has been overrun by sea-water or that has been subjected to the percolation of sea-water must inevitably contain relatively much replaceable magnesium and sodium. These results have a direct bearing upon the hypothesis of E. McKenzie Taylor with respect to the origin of oil- and coal-deposits.

In the Mid-Continent Oil-Field there are many streams polluted by waste brine from the oil-wells. Analysis of the polluted streams shows a primary salinity of 50 to 70 per cent and a secondary salinity of 30 to 50 per cent near the source of contamination. Farther down the streams, or in shallow wells near them, instances are known wherein the primary and secondary salinity are reversed, showing rejuvenation of natural base-exchange silicates in the soil with the resultant raising of the secondary salinity in the water. It may be added that these oil-field brines have been successfully used for the rejuvenation of zeolite water-softeners.

There occurs, in some localities of the Mid-Continent Oil-Field, a remarkably soft-water at depths of 250 to 600 feet. Waters found above this zone are high in temporary hardness. The soft-water carries mainly sodium bicarbonate, with only traces of calcium and magnesium. It is assumed that this water has come into contact with natural zeolites, either in filtering vertically from the surface or laterally from the outcrop, or both. Correlation of this aquifer to the outcrop or the identification of the zeolitic minerals has not been accomplished.

It is very probable that these reactions are also important in determining the character of deep subsurface-waters, although evidence of such reactions is more remote. If the brine now found in the oil-strata is really trapped sea-water, that is, "connate," then it seems reasonable to assume that the preponderance of the base-exchange reactions were those of the sodium zeolites, raising the primary salinity of the water. A somewhat opposing view postulates calcium-clays deposited in sea-water and there undergoing base-exchange. This would necessarily raise the secondary salinity of the resulting trapped water at the expense of the primary salinity.

(5) The composition of water in relation to hydrographic problems, such as the movement of underground waters

Probably the major portion of the investigational work in this field is conducted under the supervision of the United States Geological Survey in cooperation with agencies in the several states. The reports of these investigations are either published by the Geological Survey in the series of Water-Supply Papers or are catalogued in the "Index of analyses of natural waters in the United States," currently published in that series.

(6) The quality of water supplies for agricultural, domestic, and industrial use and the changes in quality consequent upon such use

This field includes a large number of active investigational projects in relation to agriculture, the mining and manufacturing industries, and sanitation, including the problems of municipal supply and stream-pollution. The reports of these investigations are in general well catalogued, as in the "Index of analyses of natural waters of the United States" and in respect to special research features in "Chemical Abstracts."

The subject of stream-pollution by mine-drainage and related problems has been under intensive investigation by the United States Bureau of Mines for the past seven years or more, and the results have been published in a series of some 20 papers.

(7) The processes and conditions occurring at the contact of land-waters with ocean-waters

Investigations in respect to this subject are currently active on both the Atlantic and Pacific coasts. Two reports on investigations on the Pacific Coast have been issued during the year by the California Division of Water Resources: "The economic aspects of a salt-water barrier below the confluence of Sacramento and San Joaquin rivers" and "Variation and control of salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay." The latter is briefly abstracted by Thomas H. Means in the accompanying Appendix A.

During the year special attention has been given, particularly in the southwestern United States, to the subject of fluorine in domestic water-supplies. The following is a brief review of the subject by H. V. Smith of the University of Arizona:

"In 1931, Smith, Lantz, and Smith published a bulletin in which the cause of mottled enamel was definitely shown to be due to the presence of fluorine in drinking-water. Chemical analyses of waters as well as feeding experiments with rats were used in the proof.

"In 1932, a report of Arizona drinking-water supplies was published by Smith and Smith. This bulletin is a correlation of the fluoride-content of the waters and the associated tooth-condition. Fluorine analyses were made by a modification of the Fairchild ferric-chloride method. Waters containing less than 2.0 parts per million did not cause the defect. Waters above 2.7 parts per million have always been asso-

ciated with mottled enamel. Forty-five communities were found in the state in which mottled enamel is endemic. Mottled enamel has been reported from at least 20 of the 48 states in the union. In Arizona, waters which contain non-toxic amounts of fluorine have been found for several of the larger towns. This work is being continued.

"One of the most important phases of the problem is the development and acceptance of an official method for fluorine. It seems that at least four methods are being used at the present time. Perhaps the most promising of these are the sulphocyanate and Steiger methods."

It is reported that a comprehensive investigation in respect to the fluoride-content of Colorado River has been inaugurated by the Metropolitan Water District of California, in connection with which it is proposed to determine also the concentrations of certain other so-called "rare-elements" that may be found in that stream.

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APPENDIX A--ABSTRACT OF BULLETIN 27, VARIATION AND CONTROL OF SALINITY IN SACRAMENTO-SAN JOAQUIN DELTA AND UPPER SAN FRANCISCO BAY, 1931

(Department of Public Works, State of California, 437 pp., 82 pls.)

Thomas H. Means

The above entitled Bulletin is the result of several years investigations on the movement of salinity by tides and river-currents in the waters draining into the Pacific Ocean through the Golden Gate.

Thirty-two thousand square miles of mountain and valley, or 39 per cent of the mountain and foothill catchment-area of the State, drain into the Sacramento and San Joaquin rivers and from the point where these rivers join to enter Suisun Bay the flow continues through Carquinez Strait into upper San Francisco Bay and eventually into the Pacific Ocean. The drainage-area includes the western slope of the Sierra Nevadas north of Kings River, a region of heavy precipitation and great annual accumulation of snow. The mean annual precipitation varies from less than 10 inches on the west side of the San Joaquin Valley to over 90 inches in the mountains.

Under natural conditions the stream-flow varies greatly as the region is one of seasonal rains. Nearly all precipitation which produces runoff comes in the cool season, November to April. Summers are nearly rainless. The streams which drain low mountains and plains vary in flow with the rain, those which drain the higher mountains rise as the warm weather melts the snow. High stream-flow therefore may result in winter from rains or in early summer from melting snow. The combined result produces flow toward the ocean from the beginning of each season's rain to the end of the snow-melting period with minimum runoff in the late summer and early fall.

Under natural conditions in low-flow periods tidal oscillations are felt in the Sacramento River to a point above the City of Sacramento (over 100 miles from the ocean) and nearly to the mouth of the Stanislaus River on the San Joaquin (about 120 miles from the ocean). Tides at Fort Point (San Francisco) have a mean range of 3.9 feet. The range throughout the Bay-region and well into the lower reaches of the two rivers continues to be large; at Collinsville, at the mouth of the Sacramento, it is 4.4 feet.

The volume of water flowing into the Delta under natural conditions approximates 31,000,000 acre-feet a season, varying between five and fifty million acre-feet. The mean daily flow at the river mouth under natural conditions varies from a few thousand second feet in the driest time of dry years to nearly a million second feet in greatest floods.

Man has produced great changes in natural conditions. Rivers no longer run as they did in nature. Over a million acres of land are now irrigated in the watershed tributary to the San Francisco Bay and over five million acre-feet are diverted in the average season. Storage-reservoirs, with capacity of over four million acre-feet, are now constructed and every major stream except the Sacramento above the valley edge has large reservoirs in operation.

The use of these facilities for diversion and storage changes in late summer. There is released only the amount of water which can be used by irrigators or power-plants. In consequence, the flow into tide-water has in late summer been reduced to a few hundred second feet and occasionally to zero, and for several months each year the flow is not great enough to prevent salt-water coming upstream with tides. Salt-water has been carried far inland each season, and large areas of land which formerly were surrounded by fresh water and were able to irrigate by opening gates at high tide or by pumping at any time are now surrounded by brackish or salt-water during the latter part of the summer. Industries and communities formerly dependent upon the streams for fresh water are now required to seek some other source of supply.

In 1918 runoff approximated 50 per cent of normal. Agriculture by irrigation was stimulated by war and in particular a large crop of rice was planted along the Sacramento River. These circumstances combined to cause unusually large diversions from the streams which were unusually low. The result was that salt-water was carried by the tides into the upper bay and lower delta-region earlier than usual and remained for a longer time attracting attention to the menace of salt-water invasion not generally appreciated before that time. Since 1920 dry years have been frequent and two years, 1924 and 1931, are record low years for both rainfall and runoff. Since irrigation above the tidal area has continued to the post-war extent and has in many regions increased, the salt-water inflow by tides has continued every year and in 1931 extended almost to Sacramento.

Early records show that Suisun Bay, into which both the Sacramento and San Joaquin rivers flow, was fresh much of the year and only for short periods in the low-flow period was salt-water present. In the driest years only did salt-water reach into the delta-lands, just above the bay. Since 1918 salt-water has gone well up both streams and in extreme years nearly all the rich delta-islands have been surrounded by water too salty to be used with safety by irrigators and in 1931 salt-water extended to within a few miles of Sacramento.

This Bulletin reports the results of a detailed study to determine the laws under which salt-water moves upstream by tidal influences and a determination of the quantity of water which must flow down stream to counterbalance the effect of tides and maintain any given degree of salinity at any point in the river and bay system.

The report contains a detailed statement of both field- and laboratory-methods used in the investigation and its reading will be interesting to anyone who has to deal with similar problems in other estuaries.

In the present investigation the study was directed to a comparison of a salt-water barrier to be built across the tidal channel to prevent the upward flow of salt-water, with storage-water release. The results show that reservoirs can be built in the mountains to release storage and maintain fresh water at the river-mouth--thus protecting the delta-lands from salt-water--cheaper and with greater assurance of success than could be done by construction of a salt-water barrier.

In connection with this study, the Salt-Water Barrier was investigated and described in Bulletin 28 of the same series.

Unfortunately neither report includes any new information upon the effects of salinity upon agriculture nor the limits of salinity which may safely be used for irrigation.

Later investigations reported in mimeographed form by the Division of Water Resources, "Sacramento-San Joaquin Water Supervisors' report for year 1931," issued August, 1932, include an estimate of crop-damage due to salt-water invasion into the agricultural area. The average loss is $356,700 for the eight years 1924 to 1931 with a maximum of $1,263,000 in 1931. If to this be added the reduction in land value and other losses of an intangible nature, the total loss will far exceed the figures given.

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THE USE OF STREAM-FLOW RECORDS IN CONNECTION WITH PROBLEMS IN HYDROLOGY

C. H. Pierce

Many of the problems in hydrology must be approached first on a qualitative basis and the phenomena investigated with reference to general relations. A qualitative analysis may be made to determine the kind and nature of the various elementary factors which directly or indirectly enter into the problem, and to arrive at the general form of the relations. For example, the qualitative form of the hydrologic cycle of water may be observed and the fact that precipitation which reaches the surface of the Earth in the several forms of rain, snow, and dew thereafter follows various paths over and through the ground, and finally, with some losses due to evaporation and plant-growth, reaches the ocean and may then complete the cycle by again returning to the atmosphere. The laws governing the movement of water from the clouds to the sea must necessarily be studied qualitatively in order to ascertain all of the factors and the manner in which they are related, one to another. But with the fundamental principles correctly established, the problem takes a quantitative form, and the definite mathematical relations can only be determined by measurements. Although the phenomena of precipitation, runoff, and evaporation are intimately connected, and interdependent, one with another, their relationships for all areas can be expressed only in general terms. The forces of evaporation are in continual operation, whereas the precipitation is intermittent. The surface-runoff is affected by loss to ground-water and by return of ground-water to surface-water flow with many variations due to seasonal and climatic conditions, soils, vegetation, and morphologic features. In general it is true that surface-runoff equals precipitation minus losses, where plant-consumption, evaporation, and transferrence to ground-water are all included in the term "losses."

These losses are variable. Evaporation may vary with temperature, air-movement, relative humidity, and possibly with other factors. Plant-consumption varies with the character of vegetation, the stage of development of the plant-growth, the temperature, and growing conditions. The loss to or return from ground-water may have seasonal changes and also variations depending upon both surface-water and ground-water conditions.

Although the various losses are difficult to evaluate individually, the total loss can be arrived at by comparisons of precipitation and runoff data for those areas which have comparable records of precipitation and runoff. The amount of precipitation on a drainage-area is usually arrived at by averaging or otherwise adjusting the observations at a few points so as to apply the data to the entire area. Records of precipitation at a fairly large number of places properly spaced over the area are desirable in order to arrive at the true average precipitation for the drainage-area as a whole.

Measurements of stream-flow for use in quantitative studies of hydrologic phenomena should show the total surface-water runoff above the place of measurement, and so far as possible, the records should be corrected so as to show the natural runoff. Many streams are now affected by storage-regulations or by divisions, and unless the effects of the regulations and diversions are known and taken into consideration, the records of runoff may not be comparable from year to year.

The water-supply papers of the United States Geological Survey contain a large amount of data relating to stream-flow. These records are being increased year by year, not only in lengths of the records, but also in the number of places where records are available.

At the present time about 2,700 gaging-stations are being maintained by the Water Resources Branch of the United States Geological Survey and records of various lengths have been obtained at about 6,600 places in the United States. The work is, in general, carried on in cooperation with State agencies as indicated on the title pages of the water-supply papers in which the records are published.

It is realized that the length and continuity of runoff records are important considerations in the use of the data for quantitative studies. Not only does the distribution of runoff throughout the year vary for different years, but the total

yearly runoff may vary widely from year to year. Mathematicians have attempted to demonstrate that the yearly runoff varies in accordance with cyclic periods. Unfortunately, the lengths of most records are too short to successfully prove or disprove the existence of mathematical cycles. However, in the instance of Lake Vänern, Sweden, with a record of stage extending over 124 years, there has been shown to be 129 cyclic periods varying in length from less than six months to about 116 years. (See "A treatise on reliable predictions of water conditions" by Ragnar Lindquist, Stockholm, 1932.)

In the United States there are very few continuous records of stream-flow at the same location which exceed 50 years in length, but these few long-time records are exceedingly valuable for the study of runoff relations. However, in comparatively few instances do the rivers now "flow unvexed to the sea." Nearly all have been affected to some extent by development and utilization. In some instances the low-water flow has been increased by the operation of storage-reservoirs, in others the flow has been decreased through diversions, and power developments have operated to change the distribution of flow. Not only have the relations of minimum, maximum, and average rates of flow undergone changes due to utilization of the rivers, but the losses attributable to evaporation, plant-growth, and transference to ground-water may have changed. The additional water-surface areas of storage-reservoirs and the effects of power-waves in spreading water over wider channel-areas for a few hours each day and then leaving these areas to drain out, with the shallow water exposed to Sun and wind, might be expected to increase evaporation-losses. The use of water by plants and the resulting losses, by transpiration, as well as the immediate evaporation of precipitation from plant-foliage, may have changed with changes in the character of the vegetation as additional areas have been cultivated or in some cases allowed to return to forest-cover. In some areas the relations of surface-water to ground-water may be immediately responsive to changes in seasonal distribution of the flow in the stream-bed. These various factors should be given consideration in studies of the quantitative relations of precipitation, evaporation, and other losses, and the residual stream-flow.

In many problems relating to hydrology it is necessary to establish average, or the most probable average, relations. In determining the average, care should be taken to see that it is for a representative period, and that the period is sufficiently long so that it includes the highs and lows in their proper proportion. It should, of course, be obvious that comparisons of data for different areas should be made on the basis of the same period.

A 53-year record of the discharge of the Merrimack River at Lawrence, Massachusetts, for the period October 1, 1879 to September 30, 1932, shows an average yearly runoff of 20.00 inches. The net drainage-area at Lawrence, after allowing for diversions taken for water-supplies, is about 4,460 square miles.

The Souhegan River, draining an area of about 171 square miles, is a tributary of the Merrimack River, joining it from the west about 25 miles above Lawrence. A 23-year record of the Souhegan River for the period October 1, 1909 to September 30, 1932, shows an average yearly runoff of 22.00 inches. For the same 23-year period the records of the Merrimack River at Lawrence show an average yearly runoff of 18.90 inches, whereas the average for the 53-year period is 20.00 inches, a difference of 1.10, or about 6 per cent. Although 23 years is generally considered a fairly long period for a record of stream-flow, yet it may be seen that another period of the same length may show very different runoff characteristics. For example, the 23-year period October 1, 1885 to September 30, 1908, shows an average runoff for the Merrimack River at Lawrence of 21.90 inches, which is a difference of 3.00 inches, or 16 per cent of the average for the 23-year period ending September 30, 1932.

These comparisons show the need for long-term records in order to determine the runoff characteristics of a drainage-basin. They also indicate the uncertainties which may occur in comparisons of the characteristics of different drainage-basins unless the comparisons are made for the same periods of time.

Reference has been made to the number of gaging-stations now being maintained by the Water Resources Branch of the United States Geological Survey. A recent count of the gaging-stations for which continuous records of daily discharge are available for

periods of ten years or longer shows the following numbers: 50 years or longer, 6; 40 to 50 years, 9; 30 to 40 years, 45; 20 to 30 years, 230; 10 to 20 years, 779.

This list has recently been revised by eliminating a number of stations where records were missing for the winter months.

It is generally true that the value of a stream-flow record not only increases with the length of the record, but that the value and usefulness of the record increase more than the proportional increment of time.

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Washington, D. C.

PRECIPITATION AND RUNOFF AND ALTITUDE RELATIONS FOR CONNECTICUT RIVER

H. K. Barrows

Synopsis--This paper discusses the amount of and variation in precipitation and runoff of the Connecticut River and its tributaries in New England and the relations of these two factors to the mean altitude of drainage-areas.

While there are numerous precipitation-stations in and near the Connecticut River Basin, only two of these are at elevations exceeding 2,000 feet, whereas the river-basin often reaches 2,500 to 3,500 feet elevation, and over 6,000 feet in the White Mountain Region. This requires therefore a consideration of station and basin altitudes in the determination of basin-precipitation. The general relations between precipitation and altitude have been studied and determined.

The United States Geological Survey has obtained and is continuing some good records of runoff, with nine main river gaging-stations and 35 stations upon tributaries of Connecticut River.

From these records the long-time mean yearly runoff has been determined for all main river- and tributary-stations, as well as the average altitude and yearly temperature for their drainage-areas. A fairly definite general relation between runoff and altitude has been determined, which will be of service in estimating the yield of areas not now gaged.

The relative consistency of the runoff records has also been studied in some detail and the long-time mean runoff of the river and its tributaries has been determined fairly accurately.

This paper prepares a foundation for further more-detailed studies of precipitation, runoff, and water-losses.

Connecticut River--The Connecticut River is the largest river lying within the New England states. It rises in the extreme northerly portion of New Hampshire, with a small tributary in Canada, and flows between the states of Vermont and New Hampshire and through Massachusetts and Connecticut--a distance of about 250 miles to the head of navigation at Hartford.

Its drainage-area (Fig. 1) is long and relatively narrow, varying from 25 to 60 miles in width and averaging about 40 miles wide above Hartford.

Its principal tributaries with drainage-areas in order from the north are:

(a) From the west--Nulhegan, 149; Passumpsic, 484; Wells, 102; White, 710; Ottaqueechee, 222; Black, 201; West, 428; Deerfield, 667; Westfield, 515; Farmington, 584; total, 4,062.
(b) From the east--Ammonoosuc, 388; Mascoma, 195; Sugar, 274; Ashuelot, 424; Millers, 346; Chicopee, 721; total, 2,396.
Or 6,448 square miles out of 10,000.

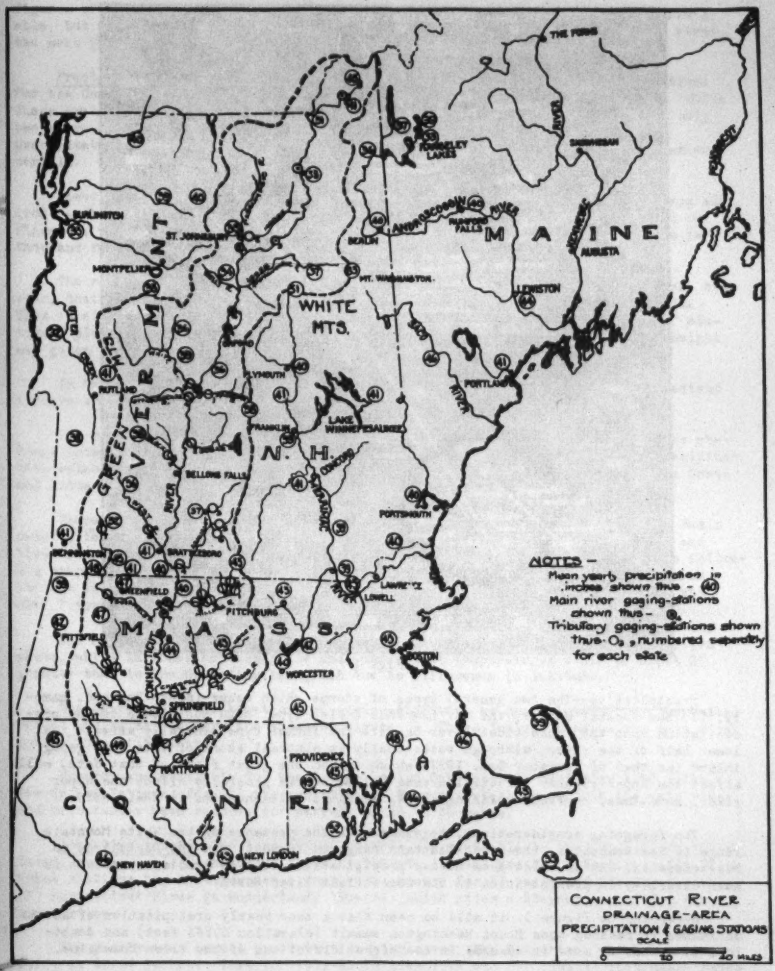


Fig. 1

With its tributaries it is an important power-stream--with over 500,000 horse-power developed and much undeveloped power.

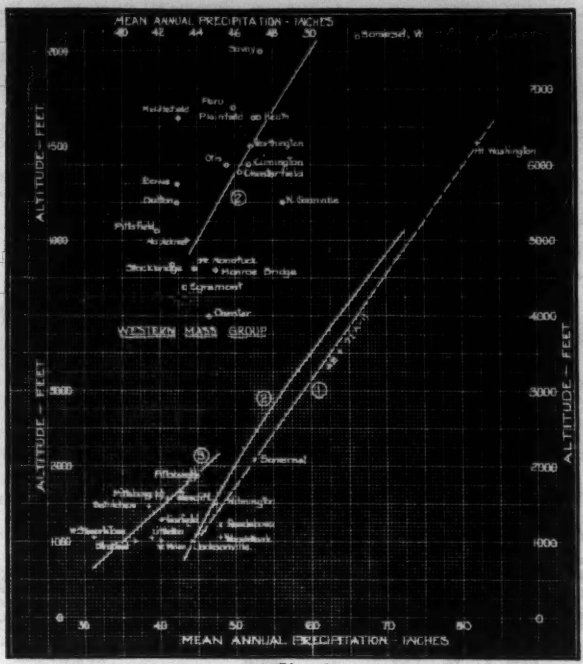


Fig. 2

Precipitation--The two general types of storms which occur in New England, namely, (1) the Coastal and (2) the St. Lawrence Valley type, both contribute to the precipitation upon the Connecticut River Basin. The former type generally affects the lower half of the river, although occasionally an abnormal storm of this type going inland (as that of November 3-4, 1927, which caused the great flood of that date) will affect the upper river. The St. Lawrence Valley storms generally affect the upper river, sometimes, however, reaching as far south as Massachusetts in their effect.

The foregoing considerations, together with the presence of the White Mountain range in New Hampshire, the Green Mountain range in Vermont, and the Berkshires in Massachusetts, all of which show marked precipitation-altitude gradients, result in much diversity in precipitation in the Connecticut River Basin.

Referring to Figure 1, it will be seen that a mean yearly precipitation of about 83 inches is reached upon Mount Washington summit (elevation 6,293 feet) and doubtless 60 inches or more is reached in the higher elevations of the Green Mountains, which reach 4,000 feet.

The lowest yearly precipitation, of about 31 inches, occurs in the rainfall-shadow area north of the White Mountains in New Hampshire and in northeastern Vermont.

The average precipitation upon many portions of the Basin can not be obtained directly from the precipitation-records alone as few stations are sufficiently high to adequately allow for the greater precipitation at the higher altitudes. No accurate

figures of average precipitation, taking into account elevation of basin, are available, but above Hartford, Connecticut, based upon the gaged runoff of the main river, the mean yearly precipitation is probably about 43 inches for the whole river.

Precipitation-altitude--On Figure 2 are shown precipitation-altitude relations for the Connecticut River Basin and vicinity above about elevation 1,000 feet. While there are many precipitation-records at elevations under 2,000 feet, there are only two above, namely, Somerset (2,096 feet) and Mt. Washington (6,293 feet). The precipitation-altitude gradient above elevation 2,000 feet is therefore somewhat uncertain.

Based upon the Mt. Washington, Somerset, and Jacksonville records--which are all good--a straight-line gradient, $P = 45 + 7 (A - 1)$, results, shown by curve (1) on Figure 2, where P is the mean yearly precipitation in inches and A the altitude in thousand feet.

The result of considerable study of both precipitation and runoff indicates, however, that a curved gradient, shown by (2) of Figure 2, is more likely to obtain. This is also consistent with the records for the western Massachusetts group of stations, plotted upon a larger scale on Figure 2. In drawing this curve, equal weight was given to the records for Savoy (2,000 feet) and Somerset (2,096 feet).

In the rainfall-shadow area of northern New Hampshire and Vermont, the gradient appears somewhat as shown by curve (3) of Figure 2.

The need of some good all-the-year records of precipitation at two or three stations between elevation 2,000 and 6,000 feet is obvious, before an altitude-precipitation relation can be established with certainty for the general vicinity of the Green and White Mountains.

Temperature--The range in elevation and latitude of the Connecticut River Basin results in some variation in mean yearly temperature. A study of temperatures and elevations at some 15 stations, including that at Mt. Washington, indicates the following temperatures for the Connecticut River Basin at about the middle of its course through Vermont and New Hampshire: Mean yearly values of 45°, 44°, 43°, 41.5, and 39.5 F for elevations of 500, 1,000, 1,500, 2,000, and 2,500 feet, respectively.

The extreme upper river would have temperatures about 1° less than those given above, while in lower Massachusetts and Connecticut temperatures would be about 2° greater than in the preceding paragraph due to difference in latitude.

Gaging-records--The locations of gaging-stations, as now maintained by the United States Geological Survey, are shown on Figure 1. These include nine on the main river and 35 upon tributaries.

Records are available for the 4-year period October 1928-September 1932 (with a few interpolations) for all these stations. Numerous stations on both the main river and tributaries have records for periods of 15 to 30 years.

Long-time runoff--Two long gaging-records are available in the Connecticut River Basin, namely: (1) Connecticut River at Orford, 1901-21 and South Newbury, 1922-32--these stations together furnish a continuous record for 32 years for the upper river; (2) Connecticut River at Sunderland, 1904-32, which gives a 28-year record for the lower river.

The yearly mean annual precipitation at Hanover, New Hampshire, which is near Orford, is 35.84 inches. That for 1901-32 is identical and for 1904-32 the same. Hence either one of these long-river gaging-records can be assumed as giving a well-defined, long-time runoff.

In Table 1 are given progressive mean runoffs for the Orford-South Newbury and Sunderland stations starting with the year 1931-32, which show the time required to establish the long-time mean and also furnish a means for determining how closely any given record-period in the basin approximates a long-time mean and the proper correction-ratio therefor.

Table 1--Connecticut River, progressive mean runoff, 1900-1932

No.	Year	Yearly runoff CSM		Progressive mean runoff CSM		Ratio of total-period mean to progressive-mean	
		Orford - South Newbury	Sunderland	Orford - South Newbury	Sunderland	Orford - South Newbury	Sunderland
1	1931-32	1.68	1.32	1.68	1.32	1.04	1.28
2	1930-31	1.18	1.32	1.43	1.32	1.18	1.28
3	1929-30	1.53	1.36	1.46	1.33	1.20	1.27
4	1928-29	1.79	1.78	1.55	1.44	1.13	1.18
5	1927-28	2.46	2.59	1.73	1.67	1.01	1.02
6	1926-27	1.46	1.44	1.68	1.63	1.04	1.04
7	1925-26	1.99	1.82	1.73	1.66	1.01	1.02
8	1924-25	1.70	1.65	1.72	1.66	1.02	1.02
9	1923-24	1.90	1.95	1.73	1.69	1.01	1.00
10	1922-23	1.53	1.40	1.72	1.66	1.02	1.02
11	1921-22	2.04	2.04	1.75	1.69	1.00	1.00
12	1920-21	1.62	1.80	1.74	1.70	1.00	1.00
13	1919-20	2.04	2.04	1.76	1.73	1.00	0.98
14	1918-19	1.99	1.80	1.77	1.73	0.99	0.98
15	1917-18	1.62	1.54	1.77	1.72	0.99	0.99
16	1916-17	1.99	1.78	1.78	1.72	0.98	0.99
17	1915-16	1.91	1.98	1.79	1.74	0.99	0.98
18	1914-15	1.34	1.29	1.76	1.72	1.00	0.99
19	1913-14	1.48	1.48	1.75	1.71	1.00	0.99
20	1912-13	2.05	1.89	1.76	1.71	1.00	0.99
21	1911-12	2.02	1.91	1.78	1.72	0.99	0.99
22	1910-11	1.29	1.10	1.76	1.69	1.00	1.00
23	1909-10	1.62	1.54	1.75	1.69	1.00	1.00
24	1908-09	1.63	1.48	1.74	1.68	1.00	1.00
25	1907-08	2.06	2.16	1.75	1.70	1.00	1.00
26	1906-07	1.61	1.49	1.75	1.70	1.00	1.00
27	1905-06	1.68	1.82	1.75	1.70	1.00	1.00
28	1904-05	1.54	1.51	1.74	1.69	1.00	1.00
29	1903-04	1.31	....	1.73	....	1.01	....
30	1902-03	1.78	....	1.73	....	1.01	....
31	1901-02	2.24	....	1.75	....	1.00	....
32	1900-01	1.98	....	1.75	....	1.00	....

It is evident from Table 1 that a 20-year period practically fixes the long-time mean and even a 10-year record defines it fairly closely.

Runoff, main river gaging-stations--In Table 2 are given data of mean runoff for the nine main river gaging-stations; also the computed runoff for the river-sections between stations. The mean elevations and mean yearly temperatures are also given.

The long-time means (column 7) are obtained from the record-period means (column 6), with the exception of the 4-year records, by applying ratios (column 8) obtained by means of Table 1. The long-time ratios for the 4-year record stations (Nos. 2, 3, 7, 9) are obtained by a consideration of such ratios for the longer-period stations (columns 8 and 9).

The stations and section runoffs were found to be rational in all cases except for station 6 at Turners Falls, which was clearly in error--about 10 per cent low--this being determined by working back from station 8 at Sunderland--the intermediate drainage-area runoff being known fairly closely from the tributary stations on Deerfield River.

Runoff, tributary gaging-stations--In Table 3 are given data similar to that of Table 2 (excepting for section runoffs) for the 35 tributary gaging-stations. These are numbered in order from upstream in each state as shown on Figure 1.

Table 2--Connecticut River runoff, main river gaging-stations

No.	Station	Drainage-area sq.mi.	Record period		Long-time runoff		Four-year period 1929-32		Section between stations			Mean elevation of drainage-area	Yearly mean temperature
			Years	Mean runoff CSM	Record-period ratio	CSM	Runoff CSM	Ratio for long-time mean	Drainage-area	Runoff CSM 4-year	Runoff CSM Long-time		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
									sq.mi.			feet	°F
1	Pittsburgh, N.H.	82	1918-32	2.55	0.99	2.52	2.63	0.96				2070	40
									715	1.94	2.04	1730	41
2	No.Stratford, N.H.	797	4 years	2.01	1.05	2.10	....	....				1750	41
									803	1.58	1.68	1620	42
3	Waterford, N.H.	1600	4 years	1.79	1.05	1.88	....	....				1620	42
									1230	1.23	1.57	1450	43
4	Orford -	(3100)											
	So.Newbury, N.H.	(2830)	1901-32	1.75	1.00	1.75	1.55	1.13				1570	43
									1290	1.47	1.86	1380	43
5	White River Jc.,Vt.	4120	1912-32	1.79	1.00	1.79	1.52	1.18				1620	43
									3130	1.38	1.45	1190	44
6	Turners Falls												
	Observed	7250	1916-32	1.51	0.99	1.50	1.40	1.07				1380	43
	Corrected			(1.66)		(1.65)	(1.47)	(1.13)					
									700	1.72	2.15	1490	43
7	Montague	7950	4 years	(1.49)	1.12	1.69	....	....				1400	43
									50	1.49	1.69	....	43
8	Sunderland	8000	1905-32	1.69	1.00	1.69	1.49	1.13				1400	43
									1740	0.98	1.44	850	44
9	Thompsonville	9740	4 years	1.40	1.18	1.65	....	....				1300	43

Table 3--Connecticut River runoff, tributary gaging-stations

No.	River and station	Drainage-area	Record-period		Long-time runoff		Four-year period 1929-32		Mean elevation of drainage-area	Yearly mean temperature
			Years	Mean runoff CSM	Record-period ratio	CSM	Runoff CSM	Ratio for long-time mean		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		sq.mi.							feet	°F
	Vermont									
1	Passumpsic-Passumpsic	423	4 years	(1.78)	1.10	1.96	....	....	....	....
2	Moose-St. Johnsbury	112	4 years	1.84	1.10	2.02	....	....	....	....
3	White-W. Hartford	687	1916-32	1.74	0.99	1.72	1.55	1.11	1600	43.5
4	Ottaqueechee-No. Hartland	221	4 years	(1.82)	1.10	2.00	....	....	1660	43
5	Black-No. Springfield	163	4 years	(1.52)	1.12	1.70	....	....	1670	43
6	West-Newfane	310	4 years	1.79	1.12	2.00	....	....	1760	42
7	Deerfield-Somerset Res.	30	1912-20	2.45	1.00	2.45	....	....	2400	39
	New Hampshire									
1	Mascoma-Mascoma	148	1923-32	1.37	1.01	1.38	1.25	1.11	1420	43
2	Sugar-W. Claremont	270	4 years	1.12	1.25	1.40	....	....	1350	43.5
3	Ashuelot-Gilsum	71	1923-32	1.67	1.00	1.67	1.36	1.23	1560	43
4	Ashuelot-Hinsdale	420	1916-32	1.45	1.00	1.45	1.12	1.29	1110	44
5	Ashuelot-Otter Brook	42	1924-32	1.57	1.00	1.57	1.30	1.21	1550	43
6	Ashuelot-South Branch	37	1921-32	1.63	1.00	1.63	1.39	1.17	1350	43.5
	Massachusetts									
1	Millers-Winchendon	80	1917-32	1.68	0.99	1.66	1.30	1.27	1130	45
2	Millers-Erving	372	1916-32	1.63	1.00	1.63	1.23	1.33	1070	45
3	Millers-Sip Pd. Br.	19	1917-32	1.58	0.99	1.57	1.09	1.44	1060	45
4	Millers-Priest Br.	19	1917-32	1.75	0.99	1.73	1.22	1.42	1150	45
5	Millers-E. Br. Tully	50	1917-32	1.67	0.99	1.65	1.14	1.46	1070	45
6	Millers-Moss Br.	12	1917-32	1.76	0.99	1.74	1.28	1.36	970	45
7	Deerfield-Charlemont	362	1914-32	2.42	1.00	2.42	2.08	1.16	2050	42
8	Ware-Coldbrook	98	4 years	1.19	1.17	1.39	....	....	1030	45
9	Ware-Gibbs Cr.	199	1913-32	1.52	1.00	1.52	1.17	1.30	940	45
10	Chicopee-Bircham Bend	703	4 years	1.15	1.30	1.49	....	....	810	46
11	Swift-W. Ware	186	1911-32	1.58	1.00	1.58	1.15	1.37	820	46
12	Quaboag-W. Brimfield	151	1910-32	1.53	1.00	1.53	1.24	1.23	860	46
13	Westfield-Knightsville	162	1910-32	1.92	1.00	1.92	1.53	1.25	1560	44
14	Westfield-Westfield	496	1915-32	1.80	0.99	1.78	1.48	1.20	1240	44
15	Westfield-Middle Br.	53	1911-32	1.91	1.00	1.91	1.44	1.32	1530	43
16	Westfield-Little R.	49	1911-32	1.93	1.00	1.93	1.59	1.21	1300	43
17	Farmington-New Boston	93	1914-32	1.91	1.00	1.91	1.52	1.25	1530	43

Similar methods to those used in Table 2 were employed in the determination of the long-time mean ratios and C.S.M.

Comparison of runoffs--In Figure 3 are compared graphically the long-time mean runoff of main river stations and tributaries. Runoff is plotted as C.S.M. (second feet per square mile) against drainage-area, and the position of each main river gaging-station and the portion and extent of drainage-area occupied by tributaries is defined by rectangles whose downstream side is at approximately the point of entrance of the tributary to the main river. The sectional runoff between the main river stations is also shown by blocks.

The diversity of runoff of the different tributaries is obvious and it is noteworthy that those from the west invariably exceed in unit-flow those from the east. The effect of the Deerfield River in suddenly increasing unit-runoff where it enters the main river, due to its relatively high yield, is also an important feature. The diagram indicates a good degree of consistency in the various records.

To test this further the runoff of ungaged areas has been computed for comparison with those gaged. This results as indicated by Table 4.

Table 4--Relative yield, gaged and ungaged areas

No.	Main river section	Gaged			Ungaged		
		Area		CSM	Area		CSM
		sq.mi.	o/o		sq.mi.	o/o	
3-4	Waterford to So.Newbury	423	34	1.96	807	66	1.37
4-5	So.Newbury to White River Jc.	687	54	1.72	603	46	2.00
5-6	White River Jc. to Turners Falls	1904	64	1.65	1226	36	1.11
6-7	Turners Falls to Montague	362	52	2.43	338	48	1.83
7-8	Montague to Sunderland	....	0	....	50	100	(1.50)
8-9	Sunderland to Thompsonville	1207	69	1.64	540	31	1.05
	Total or weighted mean	4576	57	1.75	3564	43	1.35

Including with the above the Sections 1-2 above Waterford (1600 square miles at 1.88 CSM) gives a weighted mean average, for the entire river above Thompsonville, gaged and ungaged, of 1.64 CSM, which checks closely with the runoff of 1.65 CSM at Thompsonville, as given in Table 2.

While the ungaged runoff for Sections 5-6 and 8-9 appears somewhat low, it must be kept in mind that the ungaged areas in these cases are in general for smaller streams at relatively low elevation, near the main river. A more detailed study is necessary before suggesting modifications, if any.

Runoff-Altitude--On Figure 4 are plotted for the nine main river gaging-stations, as well as intermediate river-sections, mean yearly runoff in CSM against altitude. This shows a well-defined curve or relation for the stations as gaged. The intermediate sections, as might be expected, show considerable variations.

On Figure 5 are plotted similar relations for the tributary gaging-stations, and for comparison the curve from Figure 4. Curve 1 on Figure 5 is well defined and applies in general to the various tributaries. There are, however, a group of tributaries, namely, Ashuelot, Mascoma, and Sugar rivers in southern New Hampshire and the Black and White in Vermont, which apparently, due

Connecticut										47
1	Scantic-Broad Br.	99	4 years	0.98	1.25	....	440	....	....	47
2	Farmington-Riverton	217	4 years	(1.37)	1.25	1.22	1370	....	....	44
3	Farmington-Tariffville	569	4 years	1.27	1.25	1.70	950	....	....	46
4	Hockanum-E. Hartford	75	4 years	(1.06)	1.25	1.69	450	....	....	47
5	Salmon-E. Hampton	105	4 years	(1.26)	1.25	1.31	530	....	....	47
						1.68				

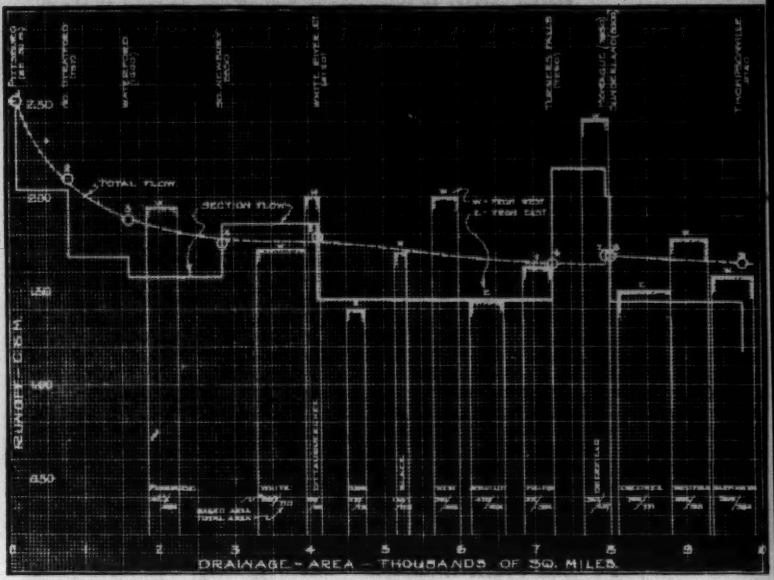


Fig. 3

to lower precipitation, show a runoff-altitude relation defined by curve 2 on Figure 5.

The great importance and effect of altitude upon runoff in the Connecticut River Basin are very apparent from these two figures.

Precipitation-runoff relations--To test the relations of the general curves upon Figures 2 and 5, the runoff-precipitation ratios and water-losses for different elevations have been determined, as in Table 5.

The runoff ratios and water-losses thus obtained appear reasonable and reflect the apparent consistency of the curves on Figures 2 and 5.

Conclusion

As a result of this study the long-time mean yearly runoff for the Connecticut River and its various tributaries has been determined fairly accurately, as well as the general relations between precipitation and runoff and altitude of drainage-area and the approximate mean temperatures. A foundation is thus prepared for further detailed studies of precipitation, runoff, and water-losses.

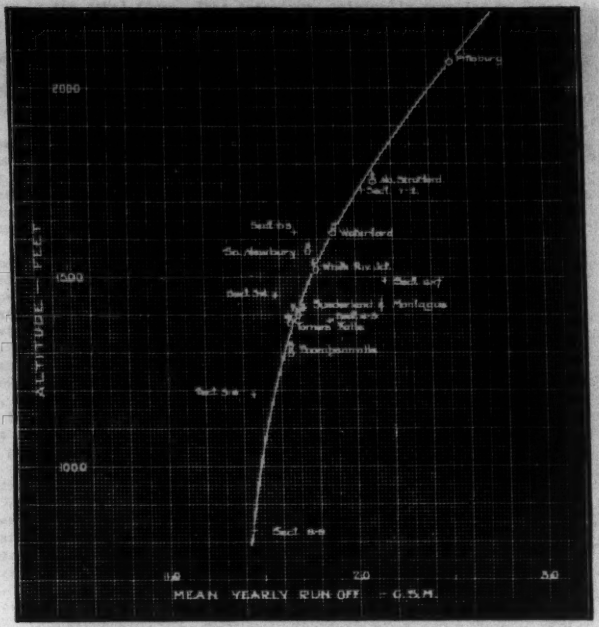


Fig. 4

Table 5--Runoff-precipitation ratios and water-losses from Figures 2 and 5

Elevation, feet	Yearly precipitation, inches	Yearly runoff		Ratio runoff precipitation	Yearly water-losses, inches
		CSM	Inches		
A--Curve (2) Figure 2 and Curve (1) Figure 5					
2000	50	2.30	31	0.62	19
1750	48.5	2.08	28	0.57	20.5
1500	47	1.89	25.5	0.54	21.5
1250	45.5	1.72	23	0.50	22.5
1000	44	1.59	21.5	0.49	22.5
B--Curve (3) Figure 2 and Curve (2) Figure 5					
1750	43	1.90	25.5	0.59	17.5
1500	40.5	1.56	21	0.52	18.5
1250	38	1.38	18.5	0.49	19.5
1000	35	1.30	17.5	0.50	19.5

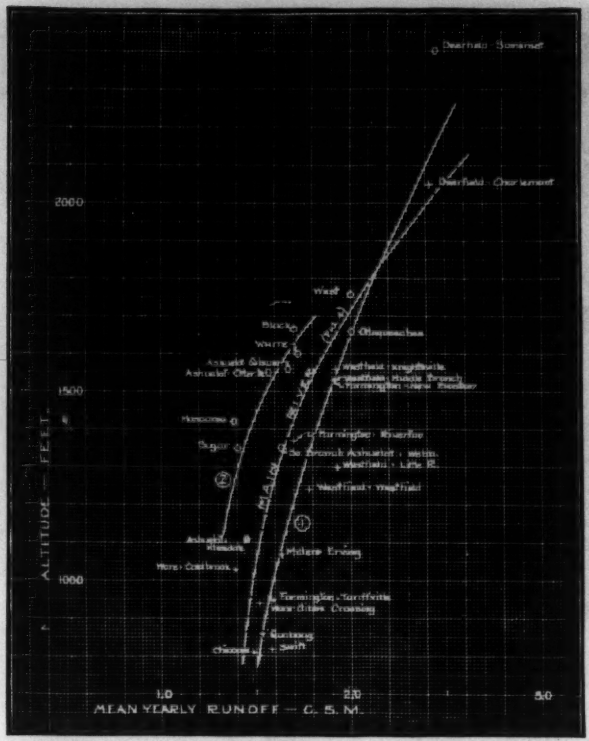


Fig. 5

6 Beacon Street,
Boston, Massachusetts

AN INVESTIGATION OF THE FLOW-DURATION CHARACTERISTICS OF NORTH CAROLINA STREAMS

Thorndike Saville and John Dargan Watson

I--INTRODUCTION

Prior to the time the Committee on Runoff of the Boston Society of Civil Engineers published their report (Report of the Committee on Runoff, J. Bos. Soc. C. E., v. 9, No. 8, 1922), duration-curves of stream-flow had been prepared almost universally by plotting the runoff in cubic feet or in cubic feet per second per square mile as ordinates against the cumulative percentage of time as abscissae. [Note: Throughout this paper the basic unit of stream-flow is defined as rate of discharge in cubic feet per second.] This report showed that if the ordinates were expressed as ratios to the mean flow, the duration-curves for different streams in New England would be surprisingly similar, regardless of any differences in the size and character of the drainage-

basin, or in the total flow. This procedure, originally proposed by Hazen (Allen Hazen, Discussion of Power-estimates from stream-flow and rainfall-data, by Dana Wood, J. Bos. Soc. C. E., v. 3, No. 3, 299-303, 1916), is confirmed by Barrows (H. K. Barrows, Water power engineering, p. 128, 1927), who maintains ".....that for the rivers of the east and south the flow, as a per cent of the mean, could be expressed, for the dryer 80 per cent of the time, by the formula $\log Q = (2.40 - 0.011\ T)$, where Q is discharge as a per cent of the mean and T is per cent of time."

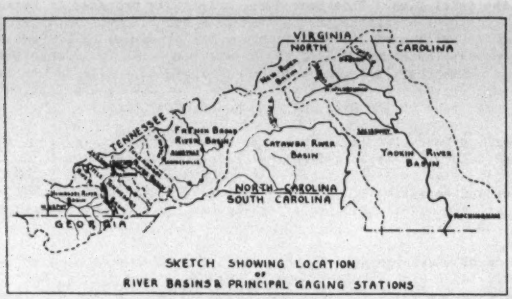
The general purpose of this study has been to determine: (a) If a significant relation appeared to exist between duration-of-flow curves of certain North Carolina streams when plotted as ratios of their respective mean flows; (b) if so, to determine the degree and variation of such relation; (c) if the relation could be expressed by Barrows' equation; and (d) if not, to develop an equation which would define any relation found to exist.

The records of discharge used in this study are all based on daily discharge recorded at official gaging-stations operated by the United States Geological Survey in cooperation with the North Carolina Department of Conservation and Development. Computations of weekly flows have been supplied by the Water Resources and Engineering Division of the latter agency. [Discharge-records of North Carolina streams, by Saville and Smith, Bulletin No. 34, North Carolina Department of Conservation and Development presents tables of monthly and weekly flow for all North Carolina streams from 1898-1923 inclusive, with drainage-area map of North Carolina and adjacent States, charts, and diagrams. Tables of weekly flow subsequent to 1923 may be obtained from the Department. The advantages of using weekly flows in hydrological studies are there pointed out, as this was the first compilation of the kind issued by any governmental agency.] The records used are as follows:

(1) Yadkin River near Salisbury, North Carolina, January 1, 1896, through December 31, 1926; 31 years; drainage-area, 3,400 square miles; mean flow, 1.47 second-feet per square mile.
(2) French Broad River at Asheville, North Carolina, January 1, 1896, through December 31, 1929, except 1901, 1902, 1903, which years of record are incomplete and were therefore omitted; 31 years; drainage-area, 949 square miles; mean flow, 2.33 second-feet per square mile.
(3) Tuckasegee River at Bryson, North Carolina, January 1, 1898, through December 31, 1929; 32 years; drainage-area, 676 square miles; mean flow, 2.48 second-feet per square mile.
(4) Little Tennessee River at Judson, North Carolina, January 1, 1897, through December 31, 1929; 33 years; drainage-area, 668 square miles; mean flow, 2.81 second-feet per square mile.
(5) Hiwassee River at Murphy, North Carolina, January 1, 1898, through December 31, 1928; 31 years; drainage-area, 410 square miles; mean flow, 2.39 second-feet per square mile.

This group was selected primarily because the discharge-record for each stream was regarded as reliable and extended over more than 30 years, and secondarily because of the rather wide variations in location, size, and character of some of the drainage-basins involved. The records for all streams except the French Broad are continuous. Figure 1 shows the location of the streams, their drainage-basins, and respective gaging-stations. All of the streams rise in the Appalachian Mountain system of North Carolina. All except the Yadkin flow west and are tributaries of the Tennessee River. The Yadkin flows southeast to the South Carolina line and thence as the Pedee River to the Atlantic Ocean. The period of record used is essentially contemporaneous for all streams.

As average weekly stream-flow was being used, and as all of the records were more than 30 years long, it would not have been practicable to plot the flow for each week for the period of record to determine the curve. It was far more convenient, and equally as satisfactory for the purpose of the study, to divide the discharge into groups and plot the group-averages. Here then a choice had to be made between equal groups of the mean and unequal groups of time, or unequal groups of the mean and equal groups of time. The former method was adopted because it enables a much greater range of stream-flow values to be plotted, and hence the resulting curve is more accurately defined by this method. [This choice is contrary to the recommendations of Dana Wood



SKETCH SHOWING LOCATION
OF
RIVER BASINS & PRINCIPAL GAGING STATIONS

Fig. 1

(Dana M. Wood, Stone and Webster Journal, February 1917, and Dana M. Wood, Discussion on rainfall and runoff studies, Trans. Am. Soc. C. E., v. 85, 106, 1922) who was one of the first men in this country to call attention to the utility of the general method of plotting in terms of the mean.] The increment adopted for the groups of ratios to the mean flow was one-tenth the mean flow.

II--TWO METHODS OF PLOTTING

There are in general use two methods for constructing a duration-table of stream-flow which is used for plotting the curve. While one method is recognized to be more conservative than the other, and in that respect superior, yet few studies have indicated the actual degree of difference between the two methods, and no previous study has dealt with the characteristics of the two methods when applied to weekly flow-data. The writers have constructed curves by both methods to determine the amount and character of the difference between them for any one stream, and to learn if the less conservative method had any advantages which would commend its use where great accuracy was not required.

The more conservative method might be called the total-period basis, but is instead referred to as the first method. Here the discharge-values are placed in order of magnitude for the entire period of record, irrespective of the calendar year in which they occurred. When this rearrangement has been made, the array is divided into groups in which the magnitude of weekly flow falls within successive values, increasing by an amount equal to one-tenth the mean flow. Thus, if the mean flow is 5,000 second-feet, as it is for the Yadkin River at Salisbury, one-tenth of this is 500 second-feet, and the first group will contain all flows from 0 to 500 second-feet, the second group from 501 to 1,000 second-feet, the third from 1,001 to 1,500, etc. The number of occurrences in each group is then counted and translated into per cents of the total time, and a cumulative per-cent of time established for plotting by methods usual in statistical work of this character. This method of grouping results in the lower 5 per cent to 8 per cent of the resulting curve being too low. The error for the streams investigated in this paper varies from 5 per cent to 10 per cent. It may be eliminated by plotting the individual weekly values for the lower 10 per cent of the time. This has not been done for the curves studied herein, as the conclusions would not be affected by it, and a considerable amount of additional work would be required.

The less conservative method might be called the calendar-year basis, but is instead referred to as the second method. Here tables are prepared giving the weekly discharge each year in descending order of magnitude irrespective of occurrence. The highest weekly discharges of each year in the total period are added, and the average determined by dividing by the number of years in the record. The same procedure is followed for the second highest weekly discharge of each year in the total period, and so on in the order of magnitude as previously set up. When these average weekly flows have been determined, they are translated into ratios to the mean flow. There being 52

weeks in a year, each one of these average weeks represents 1.923 per cent of the total time. [In a recent monograph on Duration-curves of stream-flow, the senior writer (Thorndike Saville) has denominated the second method as a Class-B, Range-I curve, and the first method as a Class-B, Range-II curve. In this monograph methods of computing and plotting duration-curves are explained in detail.]

When the two types of curves had been computed and drawn for each stream, a comparison was made between them in the following manner. Because the curves are nearly horizontal for about 80 per cent of the time, ordinates can be more accurately read from the curve than can abscissae. [Note: The curves which accompany this paper are not the original curves from which the conclusions in the paper are drawn. The original curves were plotted to different and much larger scales, so that small differences between them would be apparent.] Furthermore, it was desired to compare them in terms of stream-flow rather than time. By inspection it was seen that the general slope of the curves and the variations between any two of them were such that the deviations could best be measured by reading the ordinate for the following values of abscissae: 2.5, 5.0, 7.5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, and 97.5 per cent of time. The first average variation then is from 2.5 to 5.0 per cent of time, and the last from 90 to 97.5 per cent of time. This is done to exclude any comparison from 0 to 2.5 per cent of time and 97.5 to 100 per cent of time, for the reason that the discharge which will never be exceeded and the least discharge which will always be exceeded are indeterminate. It is also desirable to make more frequent comparisons near the ends of the curves where the curvature is changing rapidly than in the remaining portion where the curvature is relatively slight.

The second-method curve is compared with the first-method curve, and the difference in the ordinates at the selected points is designated as the ordinate-variation. The ordinate-variation is then expressed as a percentage of the first-method ordinate at each selected point, and the average percentage-variation between consecutive selected points is calculated. In this averaging, and here alone, is account taken of the sign of the variation. As the distance between the selected points does not represent equal per cents of time, these average variations must be weighted in order to determine the "variation-index" for the whole curve. An example of computations for the variation-index is given in Table 1, and the curves are shown on Figure 2. The Table and Figure are typical of results from all of the streams investigated.

Table 1--Yadkin River, first method vs. second method
(D.A. = 3,400 sq mi; mean flow = 1.47 cfs/sq mi)

Per cent time	Ratio to mean		Ordinate-variation	Per-cent variation	Average variation	Weighted average
	First method	Second method				
2.5	3.21	3.06	-0.15	- 4.7		
					2.35	5.9
5.0	2.51	2.51	0	0		
					0	0
7.5	2.12	2.12	0	0		
					0	0
10	1.87	1.87	0	0		
					0.65	3.3
15	1.53	1.55	+0.02	+ 1.3		
					1.40	7.0
20	1.32	1.34	+0.02	+ 1.5		
					0.75	7.5
30	1.06	1.06	0	0		
					0.55	5.5
40	0.87	0.88	+0.01	+ 1.1		
					1.25	12.5
50	0.74	0.75	+0.01	+ 1.4		
					1.5	15.0
60	0.64	0.65	+0.01	+ 1.6		
					1.7	17.0
70	0.55	0.56	+0.01	+ 1.8		
					3.05	30.5
80	0.47	0.49	+0.02	+ 4.3		
					7.4	74.0
90	0.38	0.42	+0.04	+10.5		
					14.6	109.4
97.5	0.30	0.35	+0.05	+18.7		
			Total.....			280.2
			Divide by 95 for variation-index...			3.0

This "variation-index" is determined and used solely as a criterion for comparing one curve with another. It will give no indication whatsoever as to the absolute deviation of one curve from another at any particular point. Take, for example, the

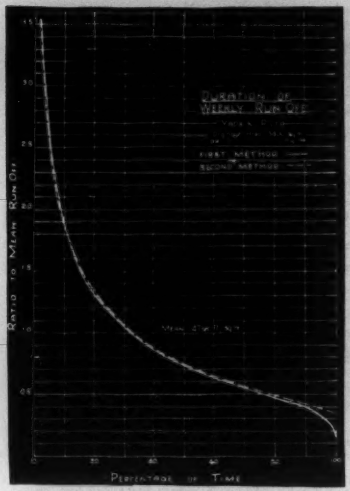


Fig. 2

Yadkin River curves (Table 1) where the per-cent variation ranges from 0 to 18.7, yet the variation-index is only 3.0. Statistically the index represents the weighted average deviation. It is essentially a measure of the closeness with which one curve approaches another as a whole.

Table 2 presents the results of computing and plotting duration-curves by the two methods, typical curves being shown in Figure 2. The variation-indices shown in Table 2 will vary from 2.8 to 4.5 when corrected for errors due to grouping. From the investigation the following conclusions may be drawn:

(a) Using the first-method curve as a base and comparing the second-method curve with it, only a small number of the deviations, or variations, are negative, and these generally on the high part of the curve, and for flows equalled or exceeded five per cent of the time. Consequently, the first-method curve is more conservative.

(b) For flows equalled or exceeded 80 per cent of the time the variations are so small as to be insignificant. For flows less than these, that is, for the drier 20 per cent of time, the variations become increasingly large, finally attaining considerable magnitude. This pronounced tendency of the second-method curve to lie considerably above the first-method curve for the drier 20 per cent of the time is the chief defect in the second-method curve. It is due chiefly to the method of averaging used in computing the second-method curve. In this method the lowest weekly flows for each year

Table 2--Comparison of flow-duration curves, first method vs. second method

River	Variation-index
French Broad	5.7
Hiwassee	5.6
Little Tennessee	4.5
Tuckasegee	3.7
Yadkin	3.0

are averaged, then the next lowest, and so on. If there is a wide spread of values within one series, the average will be very considerably higher than a good many of the lowest flows in the series. The first method avoids errors due to averaging, and errors due to grouping are not of marked significance if sufficiently small group-intervals are used. Such errors may be entirely eliminated in this method by plotting individual weekly values (ungrouped) for the lower part of the curve.

However, the second-method exhibits the following advantages, which in some cases would outweigh the lack of accuracy:

(a) The tables, once prepared, can be used again without rearrangement when additional years of record are secured. Consequently, a new up-to-date duration-table can be computed with a minimum of time and effort.

(b) As there will always be the same number of mean values, for example 52, the cumulative per-cents of time for plotting will always be the same for any stream whose record is being studied on the same basis.

(c) Should it be desired to plot the duration-curve for any single year, its record would already be arranged in order of magnitude, and the cumulative per-cents of time would be the same as for the average year, so that the plot could be made directly when the actual discharges had been translated into ratios to the mean flow.

All of these advantages would appeal particularly to agencies, mostly governmental, which are regularly engaged in the collection of stream-flow data, and which periodically publish reports of their findings.

Finally, the writers propose the following arbitrary correction for the second-method curve which will materially increase its accuracy for the drier 20 per cent of time. The correction-values, which are to be subtracted from the second-method curve-ordinates at stated per-cents of time, are the average variations of all the curves at these points. The actual values of these variations were uniformly close enough together to warrant the determination of an average value as indicated below. By use of

Cumulative per cent time									
81.73	83.65	85.58	87.50	89.42	91.35	93.27	95.19	97.12	99.04
Corrections to be subtracted from ratio to mean									
0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.12

this correction-table it is possible to prepare a duration-curve by the second-method which will very nearly equal the accuracy of the first-method, and have the added advantages of rapidity of revision and standardization of computation which are inherent in the second-method. It should be emphasized that these corrections apply strictly only to second-method flow-duration curves for the streams considered in this study, but may probably be safely used for other streams in the same region. They are corrected for errors of grouping.

The discussion in this paper relates primarily to flow-duration curves when flow-data are plotted as ratios to the mean flow. The conclusions reached in Sections I and II of the paper apply in general to any flow-duration curves, but the corrections to the second-method curve given above must be changed by multiplying by an appropriate factor if curves are plotted in other units than ratios to the mean flow.

III--COMPARISON OF CURVES FOR DIFFERENT STREAMS

Having determined a measure of the difference between the two methods of plotting, and shown the first-method to be definitely more conservative than the second, the second-method is no more used in this study, and all curves hereinafter shown have been developed by the first-method or total-period basis.

The next step was to compare the curve of each stream with the curve of every other stream, to determine the extent of the similarity, and to see if any logical interpretations could be placed upon the deviations. Table 3 and Figure 3 are presented to show the results of these comparisons.

It has not been possible to correlate definitely a low variation-index for two streams with similarities in the size or location of, or precipitation upon, their drainage-areas. In this connection the indices for comparisons involving the French Broad are not reliable, as there are 63 weeks of continuous record missing in 1902 and 1903, and four weeks in 1901. Consequently, these three years are not included in the French Broad record as used. The gaging-station has had many vicissitudes, and some of the records prior to 1917 are of doubtful accuracy. Moreover, the average rainfall on the French Broad Basin is much more variable than that on any of the others. All of these factors may explain the inconsistencies in the variation-indices where the French Broad is involved.

The lowest reliable index is for the Little Tennessee versus the Hiwassee (3.3). These rivers exhibit marked similarity in drainage-area characteristics, as do also the Little Tennessee and Tuckasegee, for which the index is also fairly low (4.8). The indices for the Yadkin River compared with others (except the French Broad) are all high (6.1 to 7.1) as would be expected, since the Yadkin differs markedly from all of the others in drainage-area characteristics. It is adjacent to, but on the other side of,

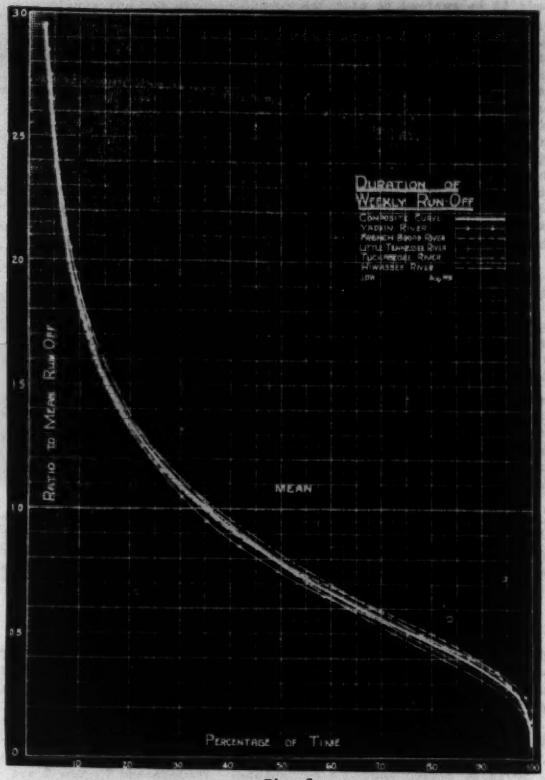


Fig. 3

the divide from the French Broad, and here the variation-coefficient is 4.4. On the other hand, the index is high (7.1) for the Tuckasegee versus the Hiwassee which exhibit a general similarity in drainage-basin characteristics. There is a reasonable presumption that some of the apparent inconsistencies in variation-indices might be explained as due to rainfall-differences on the several drainage-areas, but this subject has not been investigated. The evidence points rather definitely to generally low variation-indices for rivers having similar drainage-area characteristics, but is not conclusive.

An inspection of Table 3 reveals the fact that in half (5) of the comparisons the relation between curves for different rivers is sufficiently close to produce a general deviation of only 3 to 5, as measured by the variation-index. In the other half, where the variation-index ranges from 5.6 to 8.1, all but one relate to the French Broad (for which data are not good) or to the Yadkin (having the least similar drainage-area characteristics).

In general the relation of the flow-duration curve of one stream to that of another in the region studied will not exhibit a variation-index exceeding 5 when the

Table 3--Comparison of variation-indices

River	French Broad 31 years	Hiwassee 31 years	Little Tennessee 33 years	Tuckasegee 32 years	Yadkin 31 years	Composite curve
French Broad						
31 years	...	8.1	5.0	2.8	4.4	3.3
High 10 years	5.1	...	...	...	...	8.6
Low 10 years	5.1	...	...	...	...	7.3
Hiwassee						
31 years	8.1	...	3.3	7.1	7.1	5.0
High 10 years	...	3.2	...	...	...	6.6
Low 10 years	...	6.2	...	...	...	1.1
Little Tennessee						
33 years	5.0	3.3	...	4.8	5.6	2.4
High 10 years	...	...	11.8	...	...	15.6
Low 10 years	...	...	6.0	...	...	4.5
Tuckasegee						
32 years	2.8	7.1	4.8	...	6.2	3.1
High 10 years	...	...	...	9.2	...	6.1
Low 10 years	...	...	...	4.1	...	7.5
Yadkin						
31 years	4.4	7.1	5.6	6.2	...	3.8
High 10 years	...	...	...	...	3.8	5.6
Low 10 years	...	...	...	...	3.3	2.7
Average 10 years	...	...	...	...	4.6	...
Barrows						
Old equation	...	...	...	...	...	14.5
New equation	...	...	...	...	...	14.2
Composite equation	...	...	...	...	...	0.68

stream-flow data are reliable and the drainage-area characteristics are similar. The relation is regarded as being real and significant.

IV--COMPOSITE CURVE VS. CURVES FOR DIFFERENT STREAMS

In the previous chapter it was shown that while there is always some deviation between the curves for different streams, yet the relation in general is sufficient to be noteworthy. It would appear to warrant the determination of a composite curve. The determination of a composite curve is very easily accomplished by a summation of the number of occurrences within the several groups of per cent of mean for all five streams. This composite record totalled a period of 158 years, giving 8,216 weekly occurrences varying from 5 to 1,255 per cent of the mean. This composite curve is shown in Figure 3 together with the curves for each of the five individual streams. Table 3 shows an analytical comparison of the deviations of the individual curves from the composite curve and from each other, as measured by the variation-index. These comparisons indicate that in all but two instances each individual curve has a less average deviation from the composite curve than from any other individual curve.

This conclusion is true even for the Hiwassee River whose variation-index to the composite curve (5.0) is appreciably larger than that for any of the four other streams. Also, it is shown in Table 3 that the variation of the Hiwassee from all but one of the individual curves (Tuckasegee, Yadkin, and French Broad) markedly exceeds the variation between any other two individual curves. This consistent wide variation of the Hiwassee curves from the other curves cast some doubt upon the reliability of the Hiwassee records, which were accordingly investigated by the method developed recently by Merriam (Forecasting water-supply, A report of the Hydraulic Power-Committee,

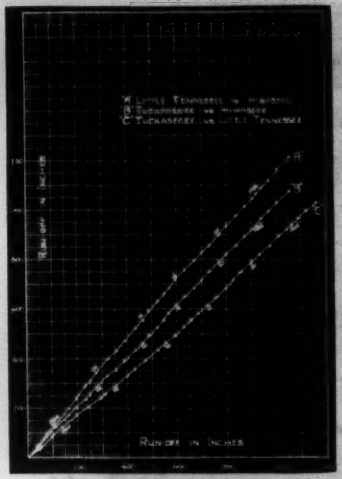


Fig. 4

N.E.L.A., March 1931). The results of the test are shown on Figure 4, and appear to indicate that the Hiwassee records are fully as reliable as those for the other streams. If this is true, some other explanation of the excessive variation in the Hiwassee curve must be adduced. Time has not permitted going further into this question, but there may be some significance in the fact that the drainage-area of the Hiwassee is appreciably smaller, and the average annual rainfall appreciably larger than those of any of the other streams investigated.

The results of this investigation lead to the conclusion that the composite curve, Figure 3, represents a more accurate delineation of the probable long-time flow-duration curve for any individual stream with more than 400 square miles of drainage-area and having its headwaters in the Appalachian Mountains of North Carolina, than does the individual curve for that stream.

V--DERIVATION OF EQUATION FOR COMPOSITE CURVE

Because of the close general agreement of one curve with another and the relationship of each with the composite curve discussed in the

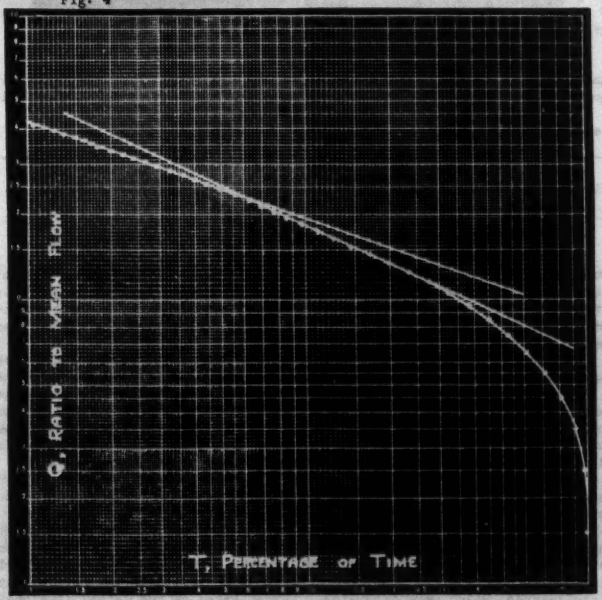


Fig. 5

preceding chapters, the determination of an equation for the composite curve appears practicable and desirable. Lipka (Joseph Lipka, Graphical and mechanical computations, p. 121) says: "The fact that a smooth curve can be drawn so as to pass very near the plotted points leads us to suspect that some relation may exist between the measured quantities, which may be represented mathematically by the equation of the curve." To this might be added the statement of Running (Theodore R. Running, Empirical formulas, p. 10): "But here we are immediately confronted with a difficulty .... one of a number of other curves might be drawn to conform quite closely to the distribution of the points. In determining the form of curve to be used reliance must be largely placed upon intuition and upon knowledge of the experiments performed."

For guidance in the selection of an empirical equation for this composite curve there are these salient facts and assumptions: (a) No part of the curve can be represented by the equation of a straight line; (b) the curve lies wholly in the first quadrant, and so all values of "x" and "y" must be positive; (c) it is assumed that there will always be some stream-flow, however small, so that while "y" may approach zero as a limit, it will never equal zero; and (d) it is further assumed that there is one maximum flow which will never be exceeded over any period of time, so that for the highest value of "y", "x" will equal zero.

Since the equation cannot be one of the first degree, the first type to consider is the simple parabolic curve, where $y = a \cdot x^b$. Lipka's (op. cit., p. 129) criterion for this type is, "If a set of data can be approximately represented by an equation of the form $y = a \cdot x^b$, then the plot of (log x, log y) approximates a straight line."

Instead of plotting (log x, log y) on ordinary coordinate-paper, the plot has been made directly on logarithmic coordinate-paper (see Fig. 5). Here it is seen that the whole plot does not even approach a straight line, but two parts of the plot can be represented by straight lines. These intersect at about six per cent of time for this set of data and for many other similar sets which were investigated. No abrupt change in slope at this point is apparent in the original curve, and its appearance in this transformation is interesting, and probably significant. An investigation of its cause is beyond the scope of this paper, but it is being studied further by the writers. Though parts of this plot approximate a straight line, this type of curve must be abandoned for this reason: If "b" were positive and "x" became zero, "y" would equal zero; if "b" were negative, "y" would be infinite when "x" became zero. This would be contrary to the fourth assumption stated above.

The next type studied was the exponential curve where $y = a \cdot e^{bx}$. This type satisfies all of the general assumptions stated above, and conforms as well to Lipka's (Ibid. p. 132) criterion: "If a set of data can be approximately represented by an equation of the form $y = a \cdot e^{bx}$, then the plot of (x, log y) approximates a straight line."

The values of (T, Q) were plotted directly on semi-logarithmic paper (see Fig. 6), first as (T, log Q), and then as (log T, Q), where T represented per cent of time and Q per cent of mean. The latter plot showed nothing. More than half the former plot closely approximated a straight line, though it is complicated by a curve at each end. In dealing with equations involving four or more constants, Lipka (Ibid. p. 152) says: "It is sometimes found that a simple equation will represent a part of our data very well and another part not at all, that is, the residuals $(y_o - y_c)$ are very small for one part of our data and quite large for another part. Geometrically, this is equivalent to saying that the plot of the simple equation coincides approximately only with a part of the experimental curve. In such cases a modification of the simple equation by the addition of one or more terms will often cause the curves to fit approximately throughout. Such terms usually have the form ce^{dx} or cd^x, and added to our simple equation give the form $y = ax^{bx} - ce^{dx}$."

It was, therefore, necessary to discard for a time the data which would not conform to the straight line, that is, up to 20 per cent and beyond 75 per cent of time, and using the data within these limits to determine the constants for the first part of the curve.

The method of least squares has not been used to determine the constants for this equation for the reason expressed by Running (Op. cit., p. 94): "In case the formula selected to express the relation between the variables is not linear the method of

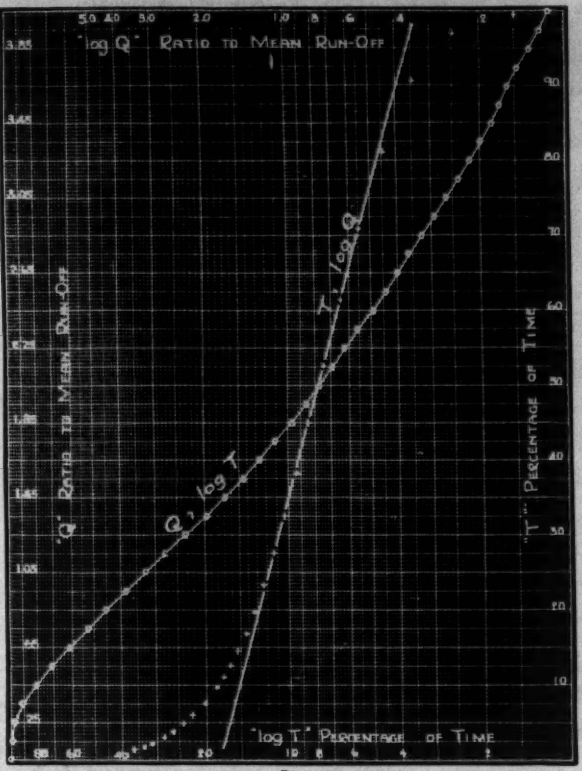


Fig. 6

least squares cannot be applied directly. In order to apply the method the formula must be expanded by means of Taylor's Theorem." Lipka (Op. cit.) uses exclusively for illustrative examples the method of averages, and that is the method used here. The data is divided into two groups and added, getting

$$7.860431 = 4 \log a + (b \log e)\ 162.603$$
$$7.653846 = 4 \log a + (b \log e)\ 189.913$$

Solving

$$b \log e = -0.007564 \text{ and } b = -0.01742$$
$$\log a = 2.272587 \text{ and } a = 187.3211$$

Therefore

$$\log Q = 2.272587 - 0.007564T$$

or

$$Q = 187.3211e^{-0.01742T}$$

The coordinates of this equation show no resemblance to the original curve except between the limits for which the determination was made, and there the agreement

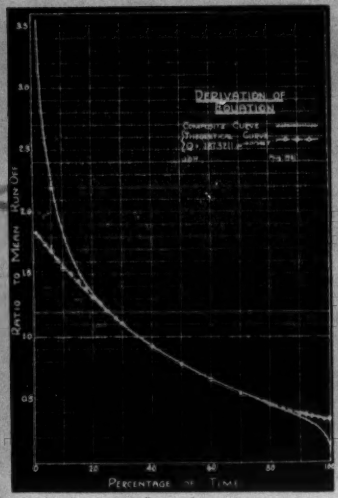


Fig. 7

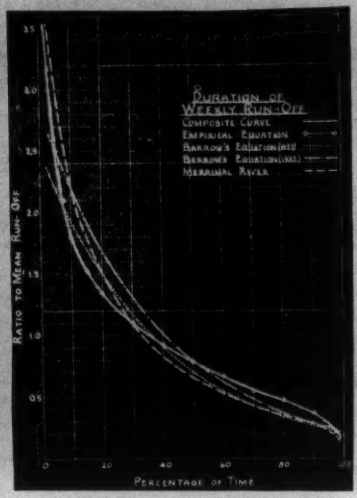


Fig. 8

is very close. Other terms must be determined and added to this equation so that close agreement will prevail over the entire range. It is seen by inspection (Fig. 7) that another term must be determined whose effect will be to increase values of "y" for all values of "x" from 0 to 20 per cent of time, and that a second term must be added whose effect will be to decrease values of "y" for all values of "x" from 75 to 100 per cent of time. Furthermore, these terms must be developed so that for all values of "x" between 20 and 75 per cent of time their effect will be negligible.

The first additional term is to be determined. With the equation already found compute values of "y" (Q) for several values of "x" (T) between 0 and 20 per cent of time, extending the theoretical curve to the left (Fig. 7). For each value of "x" (T) used, determine the difference between the actual values of "y" (Q) as shown on the composite curve and the computed values of "y" (Q). The differences are residuals "r". A plot of (x, log r) approximates a straight line, indicating that the values of "r" can be determined by the simple exponential $r = c \cdot e^{dx}$. Again using the method of averages the results are

$$7.779374 = 5 \log c + (d \log e)\ 43$$
$$6.825465 = 5 \log c + (d \log e)\ 53$$

Solving

$$d \log e = -0.09539 \quad \text{and} \quad d = -0.2196$$
$$\log c = 2.376237 \quad \text{and} \quad c = 237.8137$$

Therefore

$$\log r = 2.376237 - 0.09539T$$
$$r = 237.8137e^{-0.2196T}$$

The right-hand end of the theoretical curve is corrected in the same way and the results are

$$2.27311 = 3 \log h + (k \log e)\ 282$$
$$2.66323 = 3 \log h + (k \log e)\ 287$$

Solving $k \log e = 0.07802$ and $k = 0.17965$

$\log h = -6.57618 = 3.42382-10$ and $h = 0.0000002653$

Therefore $\log r_1 = 0.07802T - 6.57618$

or $r_1 = 0.0000002653e^{0.17965T}$

Finally $Q = a \cdot e^{bT} + c \cdot e^{dT} - h \cdot e^{kT}$

$$Q = 187.3211e^{-0.01742T} + 237.8137e^{-0.02196T} - 0.0000002653e^{0.17965T}$$

which is the equation expressing completely the composite duration curve. [It should be emphasized that the accuracy of the data does not warrant the terms of the equation being carried to so many decimal places as given above; this has been done merely to reproduce the results of the logarithmic computations.]

Such an equation as this will not yield to ready solution except in logarithmic form. This being the case each component part must be separately solved, and the several results combined for the final answer

$$Q = q^1 + q^2 - q^3 = a \cdot e^{bT} + c \cdot e^{dT} - h \cdot e^{kT}$$

Then

$$\log q^1 = \log a + (b \log e)\ (T)$$
$$\log q^2 = \log c + (d \log e)\ (T)$$
$$\log q^3 = \log h + (k \log e)\ (T)$$

As pointed out in a previous foot-note, the accuracy of the data warrants only a simple formula, which may be expressed as

$$Q = 187.3\ e^{-0.017T} + 237.8\ e^{-0.22T} - 0.00000027\ e^{0.18T}$$

and logarithmically thus

$$\log q_1 = 2.2726 - 0.00756T$$
$$\log q_2 = 2.3763 - 0.095T$$
$$\log q_3 = -6.5762 + 0.078T$$

When T becomes greater than 25, the second term "q_2" becomes less than one, and its effect from then on is negligible. The effect of the third term "q_3" is negligible for all values of T less than 85. [This term has not been corrected for errors due to grouping, which appear in the composite curve. The writers are investigating this subject further.]

Because of the complexity of the complete equation an effort was made to devise a simpler form for general use. That part of any duration-curve which represents the drier 80 per cent of time is the most useful part. Hence, it would not be illogical to discard the second term, $\log q_2 = (2.3763 - 0.095\ T)$. Then the first term, $\log q_1 = (2.2726 - 0.00756\ T)$ will closely approximate the curve between the limits of 20 and 85 per cent of time. If this theoretical curve were extended beyond 85 per cent of time to include this drier period, it would flatten out, its slope approaching zero as a limit, and it would give no true picture of the actual condition of flow. With even a casual inspection of this lower end of the theoretical curve the resemblance to the second-method curve (Chapter II) is striking. Such being the case, why not correct this curve with the same factors recommended in Chapter II? The excellent results to be secured by use of this simple expedient are shown in the following table, in which the correction-factor is taken from table in Chapter II. [The differences between the deviations and the correction-factors for the lower 5 per cent are due to corrections for grouping, which were not included in deriving the theoretical equation or in plotting the composite curve.]

Cumulative per cent of time	81.73	83.65	85.58	87.50	89.42	91.35	93.27	95.19	97.12	99.04
Equation-ordinate	0.46	0.45	0.43	0.42	0.40	0.39	0.38	0.37	0.35	0.34
Composite-curve ordinate	0.44	0.42	0.40	0.38	0.36	0.34	0.32	0.30	0.26	0.19
Deviation	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.09	0.15
Correction-factor	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.12

Thus, where it is desired to construct a duration-curve for the drier 80 per cent of the time and where time is more valuable than great accuracy, only the first term, $\log q_1 = (2.2726 - 0.00756T)$, need be used, provided the corrections given above are made. The complete theoretical curve may be readily plotted from the ordinates given in Table 4a.

Table 4a--Composite curve vs. Barrows' equation
[Barrows' equation (1927): $\log Q = (2.40 - 0.011T)$]

Per-cent time	Ratio to mean: Comp.	Ratio to mean: Barrows	Ordinate-variation	Per-cent variation	Average variation	Weighted average
2.5	3.10	2.36	-0.74	-23.9	17.0	43
5	2.43	2.21	-0.22	- 9.1	3.8	10
7.5	2.06	2.08	+0.03	+ 1.5	4.3	11
10	1.82	1.95	+0.13	+ 7.1	9.8	49
15	1.53	1.72	+0.19	+12.4	12.1	61
20	1.35	1.51	+0.16	+11.9	9.6	96
30	1.10	1.18	+0.08	+ 7.3	3.1	31
40	0.92	0.91	-0.01	- 1.1	5.1	51
50	0.78	0.71	-0.07	- 9.0	12.8	128
60	0.66	0.55	-0.11	-16.7	20.0	200
70	0.56	0.43	-0.13	-23.2	25.6	256
80	0.46	0.33	-0.13	-28.2	28.0	280
90	0.36	0.26	-0.10	-27.8	21.9	164
97.5	0.25	0.21	-0.04	-16.0		
				Total.....		1380
				Divide by 95 for variation-index.....		14.5

The Barrows equations

One of the objects of the present study was to test the applicability of Barrows' equation (H. K. Barrows, Water-power engineering, McGraw-Hill, 1927, p. 128), that is, ($\log Q = 2.40 - 0.011T$) to North Carolina streams. A plot of his curve is shown on Figure 8, together with the curve for the Merrimac River at Lawrence, the composite curve for five North Carolina rivers, and the writers' theoretical curve. The deviation between Barrows' curve and the composite curve for North Carolina rivers is very wide throughout the entire length, while the curve for the Merrimac River resembles fairly closely Barrows' theoretical curve. Table 4a gives the analytical comparison of these curves.

In a communication to the senior writer in 1932, Professor Barrows states that a later study directed by him indicates the formula $\log Q = (2.45 - 0.011T)$ to be better suited for South Atlantic streams. The curve from this equation is also plotted on Figure 8, and its variation-index computed in Table 4b.

It is apparent that neither of the flow-duration curve equations advanced by Professor Barrows are applicable to western North Carolina streams. The variation for his earlier curve is 14.5, and for his later curve asserted to be applicable to South

Table 4b--Composite curve vs. Barrows' equation
[Barrows' equation (1932): log Q = (2.45 - 0.011T)]

Per-cent time	Ratio to mean		Ordinate variation	Per-cent variation	Average variation	Weighted average
	Comp.	Barrows				
2.5	3.10	2.65	-0.45	14.50	6.22	15.5
5.0	2.43	2.48	+0.06	2.06	7.86	19.4
7.5	2.06	2.33	+0.28	13.65	16.98	42.5
10	1.82	2.19	+0.37	20.30	23.2	116.0
15	1.53	1.93	+0.40	26.10	26.02	130.1
20	1.36	1.70	+0.35	25.94	22.97	229.7
30	1.10	1.32	+0.22	20.00	15.43	154.3
40	0.92	1.02	+0.10	10.86	6.07	60.7
50	0.78	0.79	+0.01	1.28	2.39	23.9
60	0.66	0.62	-0.04	6.06	10.18	101.8
70	0.56	0.48	-0.08	14.29	16.94	169.4
80	0.46	0.37	-0.09	19.58	19.51	195.1
90	0.36	0.29	-0.07	19.44	11.72	87.9
97.5	0.26	0.24	-0.01	4.00		
			Total.....			1346.4
			Divide by 95 for variation-index.....			14.2

Atlantic streams, it is 14.2. For the lower 80 per cent and 50 per cent of the later curve the variation-index is 13.2 and 12.2, respectively, as compared with the theoretical curve deduced by the writers.

It is also of interest to note the marked difference in characteristics of flow as defined by the western North Carolina composite curve on the one hand, and on the other as defined by the curve for the Merrimac and (by inference) for other New England streams by Barrows' first equation. The North Carolina streams are seen to retain a markedly higher proportion of the mean flow during most of the drier 50 per cent of the time. Since their unit-runoff is also higher, their relative attractiveness for power development and water-supply purposes is evident. The sharp downward trend of the western North Carolina composite curve for the lowest 3 per cent of the time as compared with the Merrimac and Barrows' curves may be due to the effect of the glacial soils of New England in contributing larger relative amounts of ground-water during severe droughts than the clay soils of North Carolina. In part it is also due to the method of grouping used, as explained previously.

The first conclusion from this portion of the study is that generalized flow-duration curves, or equations for such curves, are applicable only to rather restricted regions. Just how large such a region may be requires investigation of the kind reported in this paper. Studies of daily duration-curves by the senior writer and Professor Fred Merryfield have indicated that a composite curve for the same western North Carolina streams is less applicable to the Chattahoochee River in Georgia, the Roanoke River in eastern North Carolina, and the Susquehanna River in Pennsylvania, although for the first two of these streams the North Carolina composite curve is more accurate than the curve from Barrows' equations. Of course, in generalizations of this sort, everything depends upon the degree of accuracy desired, and as a rough guide Barrows' equations are useful. They depict more accurately the flow-characteristics of Northeastern than of Southeastern streams.

The second conclusion is that the method of comparing duration curves described herein will indicate whether or not stream-flow data from a number of streams may be reasonably combined to produce an artificial record of great length. Such a procedure has been adopted in statistical studies by Hazen, Fuller, Sudler, and others. It is believed that when the variation-index exceeds 8 or 10 the flow-characteristics of a stream are not sufficiently comparable to be used in statistical studies. The writers believe that the variation-index is superior to the standard deviation as a measure for the purpose indicated, but the subject is being further studied.

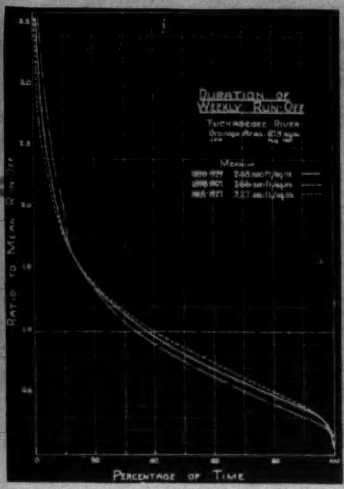


Fig. 9

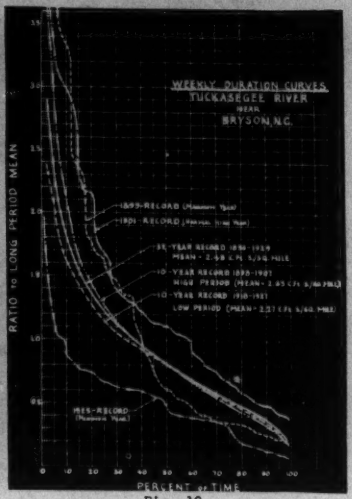


Fig. 10

VI--LONG-PERIOD CURVES VS. TEN-YEAR CURVES

Very rarely is a hydraulic engineer fortunate enough to have available a long runoff record (30 years or more) at the site in which he is interested. Many times he would consider himself lucky to have a record of ten years' duration, yet having that he is at a loss to know how much to depend on it. It might be that the 10-year period covered by a given record was one of exceptionally high or exceptionally low flow. How might he use this data and reduce to a minimum the errors in the resulting calculations?

For each of the streams studied the 10-year periods having the maximum and minimum means were picked out and investigated as individual records. In the case of the Yadkin River the high 10-year period used was not the maximum, although it was close to it. In Table 3 there will be found a comparison of these maximum and minimum 10-year curves with the long-period curve for the same streams and with the composite curve, as measured by the variation-index. A typical graphical comparison is presented on Figure 9.

In the case of the Tuckasegee River (Figure 9) the long-period (32 years) mean flow was 1,670 second-feet. The high 10-year period had a mean of 1,780 second-feet, and yet the duration-curve for this short period was for a large part of the time below the duration-curve for the long period. Similarly the minimum 10-year period which had a mean of only 1,530 second-feet presented a curve which in its significant portions was above the long-period curve. This paradox was found to be true in every case except the Hiwassee River, and even there the minimum-period curve is above the maximum and long-period curves for the lower 35 per cent of time.

The phenomenon described in the preceding paragraph is explainable in large part as due to the relative magnitudes of the three different means for the total, maximum 10-year, and minimum 10-year periods, respectively, as compared to the average and low flows in those series of years. For instance, the mean flow for the minimum 10-year period is usually made up of (a) two or three years of extraordinary low flow during the summer and fall, (b) one or two years with rather high flows during the spring, but with normal or low flows during the fall, and (c) the remaining years departing not far

Table 5--Comparison of duration of flow-data for different streams

(Little Tennessee River near Judson, North Carolina)

Ratio to mean	10-year maximum		10-year minimum		33-year average		
	No. of occurrences	Cumulative occurrences	No. of occurrences	Cumulative occurrences	No. of occurrences	Cumulative occurrences	Cumulative occurrences ÷ 3.3
0-0.1	0	0	0	0	0	0	
0.1-0.2	22	22	7	7	20	20	6
0.2-0.3	55	77	16	23	83	103	31
0.3-0.4	53	130	46	69	175	278	84
0.4-0.5	29	159	55	124	166	444	135
0.5-0.6	46	205	33	157	146	590	179
0.6-0.7	41	246	47	204	145	735	222
0.7-0.8	44	290	41	245	137	872	264
0.8-0.9	46	336	40	285	115	987	299
0.9-1.0	27	363	39	324	117	1104	315
1.0-1.1	20	383	37	361	104	1208	365
1.1-1.2	19	402	20	381	68	1276	386
1.2-1.3	17	419	18	399	69	1345	408
1.3-1.4	8	427	18	417	54	1399	424
1.4-1.5	11	438	15	432	60	1459	442
1.5-1.6	14	452	8	440	33	1492	453
1.6-1.7	5	457	15	455	27	1519	460
1.7-1.8	6	463	11	466	21	1540	467
1.8-1.9	3	466	6	472	25	1565	474
1.9-2.0	4	470	9	481	9	1574	477
2.0-2.5	14	484	18	499	64	1638	496
2.5-3.0	12	496	14	513	25	1663	504
3.0-3.5	7	503	3	516	21	1684	510
3.5-4.0	3	506	3	519	8	1692	513
4.0-4.5	3	509	0	519	8	1700	515
4.5-5.0	3	512	0	519	3	1703	516
5.0-5.5	3	515	1	520	3	1706	517
5.5-6.0	3	518	..	...	3	1709	518
6.0-6.5	1	519	..	...	2	1711	518
6.5-7.0	0	519	..	...	3	1714	519
7.0-7.5	0	519	..	...	1	1715	519
7.5-8.0	1	520	..	...	0	1715	519
8.0-8.5	..	...	..	...	0	1715	519
8.5-9.0	..	...	..	...	0	1715	519
9.0-9.5	..	...	..	...	1	1716	520

$$\frac{\text{Maximum 10-year mean}}{\text{33-year mean}} = \frac{2230}{1877} = 1.19; \quad \frac{\text{minimum 10-year mean}}{\text{33-year mean}} = \frac{1600}{1877} = 0.85$$

from normal throughout. The mean for the period is low as compared to the long-term mean, but the ratio of the individual lower 50 per cent of the flows to the mean flow is higher than in the long-period series, for in the latter the low flows may not in absolute magnitude be much below those for the minimum 10-year period, but the high flows are higher. Hence, with the lower mean, the lower end of the minimum-period curve will be above that of the long-period curve, and conversely for the upper portion.

The phenomena are well exemplified in Table 5. It is seen that there are more flows less than 170 per cent of the mean in the maximum than in the minimum 10-year period. Similarly there are more flows less than 90 per cent of the mean in the 33-year period than in the 10-year minimum period, and therefore the 33-year curve will fall below the minimum 10-year curve for the lower 90 per cent of the time.

Where the 10-year maximum and minimum curves are plotted in terms of the long-term mean, these phenomena are still present, but are much less pronounced. This is shown for the Tuckasegee River on Figure 10.

On the Yadkin River a third 10-year period, one whose mean (4,990 second-feet) almost exactly equalled the mean of the long-period (5,000 second-feet), was studied in addition (see Table 3). Using the variation-index as a criterion, it is surprising to see that there is more variation for this curve than there is for the maximum or minimum 10-year curves.

All of the above discussion leads to the conclusion that the shape of a duration-curve, when plotted in terms of the mean flow, is affected little by the absolute magnitude of the flows, but is chiefly a function of the distribution of the individual flows with relation to the mean flow for the period covered by the data. This is one of the principal advantages of plotting duration-curves in terms of the mean flow. The shape of such a duration-curve from a 10-year record will not vary greatly from the long-term curve, but the 10-year mean may vary from 15 to 20 per cent above or below the long-term mean.

The unreliability of single years of record as picturing either average flow or normal distribution of flow is strikingly illustrated by curves for the Tuckasegee River, shown on Figure 10. All of the curves are plotted in terms of the long-term (32-year) mean. It will be seen that the duration-curve for the highest year of record (1899) lies below the average period curve for 57 per cent of the time. This is due, of course, to effects of several floods in raising the mean for the year, but not affecting the rather abnormally low flows of the fall. This phenomenon is not observed in the case of a maximum year on any other stream, but other years of large total flow on such streams do exhibit it. It will be evident that the distribution of flows in any single year is most unlikely to simulate that for a long period of years, even when the single year happens to have a total flow equal to the average for the long period.

From Table 3 it is apparent that the variation-index for 10-year period curves as compared with the composite curve is generally larger (8 out of 10) than the index for the long-term curves compared with the composite.

The authors conclude, therefore, that the composite curve will more accurately represent long-period duration-of-flow characteristics of streams rising in the Appalachian Mountains of North Carolina and having drainage-areas in excess of 400 square miles than will the duration-curves for the individual streams if based on less than 30 years of record. It seems probable that as the composite curve includes a greater variety of data representing more diverse hydrological events than have occurred on any one river, but which may reasonably be expected on all, this curve represents more nearly the true average curve for any single river than any other curve which can be devised.

However, when it is realized that the comparisons are for extreme values (that is, maximum and minimum 10-year periods) the range of variation-index from 3 to 12, averaging 5.8, is surprisingly small. On the average, duration-of-flow curves based on 10 years of record, will probably not vary on the whole more than 5 per cent to 7 per cent from a 30-year curve, when plotted in terms of the mean flow. It should be realized, however, that the 10-year mean will often vary much more than this (from 15 to 20 per cent) from the long-term mean. Therefore, to use either 10-year curves or the composite curve with maximum accuracy requires an estimate of the long-term mean.

In this connection considerable effort has been directed toward methods for determining the most probable value of the long-term mean from records of ten years and longer. The application of the usual procedures of statistical methods based upon determination of the standard error of the mean have been very disappointing. From cursory examination of the form of frequency-curve developed by weekly stream-flow, it would appear that such methods should be applicable. The composite frequency-curve for the five streams investigated is shown in Figure 11. However, analysis thus far indicates that calculation of standard errors of 10-year or longer means provide no satisfactory method of approach to determining even approximately the true long-term mean. The subject is being investigated further and will form the subject of a future paper.

VII--CONCLUSIONS

As a result of the studies reported in this paper, the following general conclusions are presented:

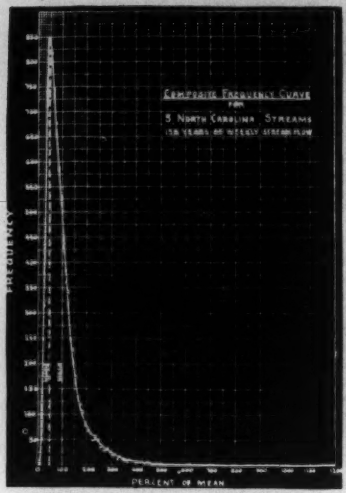


Fig. 11

(1) When plotting duration-curves of average weekly stream-flow, the total-period basis gives results which are more accurate than the calendar-year basis. Curves plotted from the calendar-year basis will depart on the average 3 per cent to 5 per cent from those plotted on the total-period basis. If plotted in terms of group means the lower 10 per cent of the total-period curves will be too low, but may be corrected by plotting the individual weekly values for the lowest 10 per cent of the time.

(2) There are certain advantages in the calendar-year basis, which are mentioned in the text. This method may be used for plotting the lower 80 per cent of the curve with an accuracy essentially equal to that of the total-period basis provided that corrections given in a table contained in the text are applied to the lower 20 per cent of the curve.

(3) For the five western North Carolina streams studied, a marked similarity in duration-curves is exhibited when such curves are plotted in terms of ratio to the mean flow. A "variation-index" is derived to measure the average per-cent variation of one curve from another. It is shown that in general, when stream-flow data are reliable and drainage-area characteristics are similar, one curve will not vary on the whole from another by more than 5 per cent. The absolute range of the variation-index for the streams investigated was from 3 to 8.

(4) The shape of the duration-curves for North Carolina streams, whose headwaters are in the Appalachian Mountains and whose drainage-area exceeds 400 square miles, is such as to indicate that their composite curve represents a more accurate delineation of the probable long-time duration-curve for any individual stream than does the individual curve for that stream.

(5) The equations of Barrows will not satisfactorily represent the duration of flow of North Carolina streams. However, the duration of flow of North Carolina streams is such as to present a smooth composite curve which can be accurately defined by the following equation

$$Q = 187.3e^{-0.017T} + 237.8e^{0.22T} - 0.00000027e^{0.18T}$$

The first term of this equation, expressed logarithmically, is $\log Q = (2.2723 - 0.00756T)$, when T is per cent of time and Q is per cent of the mean flow. This fits the composite curve between 20 and 85 per cent of the time, and fits the lower 80 per cent of the curve much better than Barrows' equations. A table of corrections is given whereby this equation may be used and the lower 15 per cent of the curve corrected from the table.

(6) Generalized flow-duration curves, or equations for such curves, are applicable only to rather restricted regions. Studies similar to those reported in this paper are required to define the extent of such a region. Such studies also indicate limitations which ought to be imposed upon artificial long-term records computed by using flow-data from a number of streams.

(7) The shape of a flow-duration curve, when plotted in terms of the mean flow, is little affected by the value of the mean for the period of record, but is chiefly a function of the distribution of the individual flows with relation to the mean.

(8) If the flow-record of any stream covers only a short period of time (less than 15 years), the duration-curve from such a record is likely to differ 5 per cent to 10 per cent from the long-time (greater than 30 years) curve for the same stream. In such a case the composite curve will again represent a more accurate delineation of the probable long-time duration-curve than a curve based on the original record itself.

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THE UPPER CONGO RIVER DRAINAGE-BASIN

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During the period 1920-30, the engineering organization of which the writer is a member carried out certain work for the Union Minière du Haut-Katanga, a mining company, in the Katanga District of the Belgian Congo in Africa. As a part of this work, a number of rainfall and river gaging-stations were established on the Lualaba and Lufira rivers to assist in the determination of the water-power possibilities on these tributaries of the Congo River.

Since climatic and physical conditions in the Katanga District are somewhat different from those encountered in this part of the world, it was thought that some of the information gathered would be of interest to the members of the Section of Hydrology of the American Geophysical Union.

The Congo River drains about 1,500,000 square miles of the central African continent. Its source is said to be in the Chambezi River, a tributary of the Luapula, in British territory, and this was discovered by Livingstone in 1867. He mistook it for the then undiscovered source of the Nile.

The Congo River proper is formed by the confluence of the Lufira and Lualaba rivers in the Katanga District of the Belgian Congo. The Congo River proper is about 3,000 miles long and has a fall of about 3,000 feet in this distance. Its lower reaches are from 20 to 30 miles wide and it is said to be second only to the Amazon in volume of discharge.

The Congo River is naturally navigable for only about 200 miles, the first falls occurring at that distance from its mouth. It is navigable in sections for some 2,000 miles, below and above the various falls occurring in the River.

The whole Congo Basin consists of a series of plateaus separated by concentrated declivities where the River tumbles over falls and rapids in short distances. This is also true with respect to the basins of the Lualaba and Lufira, each of these having a fall of about 1,000 feet. In the case of the Lualaba, this fall of about 1,000 feet occurs in a gorge, known as N'Zilo, in a distance of about 30 miles. The Lufira has two concentrated falls, one of about 400 feet in a mile at Muadingusha, and another similar one about 100 miles downstream.

The upper Lualaba and Lufira rivers are between 10° and 12° south of the equator, at elevations of 3,500 to 5,000 feet above sea-level. Altogether, the climate of the Upper Katanga District of the Belgian Congo is agreeable and generally healthful, considering its proximity to the equator. With proper care the white man can get along very well. During the midwinter months of July and August the nights and early mornings are quite cold, the temperature at times dropping to 40° or 50° F. At midday it gets quite warm, the temperature reaching 90° to 100° F from noon to 2 p.m., but, owing to the dry atmosphere at this season, hard work can be carried on without much discomfort. The winter months, from May to September, constitute the dry season, during

which it never rains. The rainy season begins gradually with a few localized thunder-storms in October. These thunder-storms become more severe as the spring advances, and when the heavy rains begin in late November or early December, the thunder-storms cease. December, January, February, and March are the wettest months, during which it rains much of the time. The rains make the climate quite agreeable in the summer time as they greatly modify the temperature, making the nights pleasantly comfortable.

A heavy grass grows rapidly after the rains begin, making the country almost impassable in many places by late December, and when it is necessary to pass through it, the process becomes more disagreeable after each rain. By February, the grass has grown very thick and tall, reaching heights of five to six feet in places. This grass becomes dry by June and must, in most places, be burned before it is possible to travel over the country freely.

The country generally is covered by park-like forests, consisting mostly of teak and scrub mahogany. There is also, however, a variety of soft timber which has various native names, which can not be classified. Very little of the Katanga timber is of merchantable quality, but it can be used for certain purposes. Timber used, unless treated, is soon destroyed by the white ants which exist in great numbers in this section. The forests are kept clean of dead wood by the white ants, and of underbrush by the many grass fires set during the dry season. There is no danger of forest fires, because of the absence of dead wood and underbrush; as without these the grass fires travel so rapidly that the standing timber seldom gets hot enough to start burning. There are no strong winds during the dry season and even the slightest breeze is seldom experienced during this period of the year.

The soil generally is a laterite with very little humus in the top soil. It is not suitable for the cultivation of crops except in a few spots where soil- and moisture-conditions are favorable.

The native population of the Katanga District is sparse and physically these natives rank amongst the most inferior on the Continent. The sterility of the soil and the Arab slave-trade carried on to within recent years in this section, are undoubtedly jointly responsible for this.

Wild animal life exists in great numbers in the Katanga.

The most recent water-power statistics available place about 47 per cent of the world's water-power in Africa. Most of this is located on the Congo River and its tributaries. In the upper tributaries, constant output of water-power in any large quantities can be developed through means of storage only, since the distribution of rainfall throughout the year is most unfavorable from a water-power standpoint. The average yearly rainfall is about 50 inches, but practically all of this occurs in from six to seven months so that during the five to six dry months the rivers are entirely dependent upon ground-water for their flow. A very substantial stream-flow is maintained in these rivers at the end of the dry season.

At the N'Zilo gaging-station on the Lualaba River which we established in 1920, where the drainage-area is about 6,560 square miles, the minimum stream-flow in eight years has varied between 750 and 1,200 cubic feet per second.

The average yearly runoff is very low, being about 15 per cent on the Lualaba and somewhat less than 10 per cent on the Lufira River.

No great floods have occurred, the maximum flow on the Lualaba at the N'Zilo gaging-station mentioned above having been 12,500 cubic feet per second, or somewhat less than two cubic feet per second per square mile of drainage-area.

The first river gaging-station was established in July, 1920, on the Lualaba River. This was located just above the entrance to N'Zilo gorge and has been named N'Zilo gaging-station. Daily gage-heights for this station are available from July 22, 1920 to August 31, 1928.

The first meter-measurements were made in the dry season and were made with a standard Price current-meter such as is generally used in this country for similar work. Two of these instruments formed a part of the writer's baggage on this trip to Africa.

A contract was made with one of the nearby native chiefs to construct a fairly large native dugout from which the meter-measurements were made during low-water stages.

At a later time a cable was erected across the River and high-water measurements were made from a cable car. In all, eleven meter-measurements were made during 1920, 1921, and 1922. The lowest discharge measured amounted to about 870 C.F.S. and the highest about 8,000 C.F.S.

The total range of discharge of the River was very completely covered by the eleven meter-measurements, thus obtaining a very accurate rating-curve.

Table 1 gives the average monthly discharge for this gaging-station for the period during which gage-records were kept under our supervision.

Table 1--Average monthly discharge in C.F.S., Lualaba River at N'Zilo gorge
(Drainage-area = 6,560 square miles)

Month	1920	1921	1922	1923	1924	1925	1926	1927	1928
January	....	3330	5800	2535	6430	3000	5220	4140	3930
February	....	5900	4790	4325	8045	3270	6500	5310	7300
March	....	9570	7810	5140	5400	6510	7770	8375	10600
April	....	7160	5270	7520	7150	6950	7750	7750	8925
May	....	3780	3440	4290	3660	4100	4540	4290	4420
June	....	2830	2535	2880	2760	2830	3360	3280	3285
July	....	2085	2015	2260	2200	2280	2760	2660	2420
August	1140	1635	1580	1760	1770	1790	2215	1965	1640
September	872	1295	1230	1360	1380	1500	1815	1270	....
October	980	1120	1195	1040	1365	1460	1540	1120	....
November	1220	1385	1345	1530	1520	1775	1805	1265	....
December	2860	2650	1805	3690	2505	3220	2640	2280	....

Table 2--Total monthly rainfall in inches,
Lualaba River at N'Zilo gorge

Month	1922	1923	1924
January	7.29	5.62	10.68
February	8.64	9.89	8.72
March	6.74	6.57	8.41
April	2.15	Missing	0.80
May	0	0.28	0
June	0	0	0
July	0	0	0
August	0	0	0
September	0	0	....
October	4.22	4.59	....
November	7.15	5.10	....
December	4.25	10.80	....
Total	40.44	.....	....

During the latter part of 1921 we established a standard rain-gage at N'Zilo and reliable daily records are available for this station from January, 1921, to May, 1924. These daily records were actually kept until August, 1928, but for some reason the readings since the dry season of 1924 are, unfortunately, unreliable.

Table 2 gives the monthly rainfall at N'Zilo for the period January, 1922, to May, 1924.

Table 3 gives the monthly runoff from the Lualaba drainage-area above the N'Zilo gaging-station in inches depth over the area.

Table 3--Runoff in inches on drainage-area, Lualaba River at N'Zilo gorge
(Drainage-area = 6,560 square miles)

Month	1920	1921	1922	1923	1924	1925	1926	1927	1928
January	.....	0.586	1.02	0.445	1.13	0.528	0.920	0.729	0.690
February	.....	0.936	0.760	0.685	1.26	0.512	1.03	0.843	1.20
March	.....	1.68	1.38	0.903	0.950	1.15	1.37	1.47	1.86
April	.....	1.22	0.897	1.28	1.22	1.18	1.32	1.32	1.52
May	.....	0.665	0.605	0.754	0.643	0.721	0.797	0.760	0.776
June	.....	0.482	0.431	0.489	0.469	0.482	0.572	0.557	0.558
July	.....	0.361	0.354	0.397	0.388	0.396	0.485	0.467	0.426
August	.....	0.288	0.278	0.309	0.310	0.314	0.389	0.345	0.289
September	0.148	0.220	0.210	0.231	0.235	0.255	0.309	0.216	.....
October	0.172	0.197	0.210	0.183	0.740	0.257	0.270	0.197	.....
November	0.206	0.237	0.229	0.260	0.259	0.302	0.306	0.216	.....
December	0.503	0.466	0.318	0.649	0.441	0.566	0.463	0.400	.....
Total	.....	7.34	6.69	6.58	7.54	6.66	8.23	7.52	.....

Table 4--Average monthly discharge in C.F.S.,
Lufira River at Tatalias
(Drainage-area = 3,700 square miles)

Month	1920	1921	1922	1923	1924	1925	1926
January	....	1630	2240	1480	3195	635	2090
February	....	4300	2147	3665	2972	1265	3870
March	....	4090	3450	4120	2280	3341	3740
April	....	3210	1800	4015	2542	2395	3840
May	....	1395	935	2290	980	935	2075
June	....	800	690	1117	710	596	1030
July	....	527	576	840	590	500	795
August	....	451	485	658	515	430	642
September	328	373	400	544	445	382	533
October	321	322	462	436	427	374	448
November	400	426	415	454	466	382	473
December	1110	1380	750	2042	689	1116	1320

A river gaging-station was established on the Lufira River in September, 1920, near the location of a contractor's camp, who at that time dredged sand from the River for use on construction work the mining company was carrying on at Panda. The contractor's name was Tatalias and the gaging-station was named after him. He arranged to have daily readings taken while his work continued at this point. After he left, natives who were trained to take the readings were stationed here as well as at the other gaging-stations. The stations were visited by an engineer from time to time to make a check on the elevation of the staff-gages and on the work of the natives, as well as to obtain current-meter measurements at various stages of the River.

After carrying out some field work along this River and in more detail at the Muadingusha Falls about 30 miles downstream from the Tatalias Camp, where the location of a hydro-electric plant was under consideration, it was realized that the flow at Tatalias might not be indicative of the flow at Muadingusha. The country upstream from Tatalias consisted of timbered highlands and heavy soil, whereas the country between Tatalias and Muadingusha consisted largely of open lowlands, somewhat swampy, through which the River meandered endlessly.

A second gaging-station was established on the Lufira River a short distance above Muadingusha Falls in November, 1921. A rainfall station was also established on the Lufira River drainage-basin at Panda in 1920. Panda is located about 15 miles due west from the Tatalias gaging-station.

Table 4 gives the average monthly discharge for the Tatalias gaging-station from September, 1920, to January, 1927. Table 5 gives the monthly rainfall at Panda for the

period September, 1920, to September, 1924. Table 6 gives the monthly runoff from the Lufira drainage-area above Tatalias gaging-station in inches depth over the area. Table 7 gives the average monthly discharge from the Muadingusha gaging-station from December, 1921, to January, 1927. Table 8 gives the monthly runoff from the Lufira drainage-area above Muadingusha gaging-station in inches depth over the area.

Table 5--Total monthly rainfall in inches, Lufira River at Panda

Month	1920	1921	1922	1923	1924
January	.....	8.20	10.54	9.21	13.90
February	.....	14.44	9.65	13.54	4.94
March	.....	12.87	6.70	17.12	9.79
April	.....	2.96	1.08	9.37	2.69
May	.....	0	0.40	0	0
June	0	0	0	0	0
July	0	0	0	0	0
August	0	0	0	0	0
September	0	0.33	0	0.03	.....
October	4.57	0.62	1.97	1.03	.....
November	4.02	5.39	6.14	3.29	.....
December	12.97	12.56	10.04	13.82	.....
Total	.....	57.37	46.52	67.41	.....

Table 6--Runoff in inches on drainage-area, Lufira River at Tatalias
(Drainage-area = 3,700 square miles)

Month	1920	1921	1922	1923	1924	1925	1926
January	.....	0.508	0.698	0.460	0.994	0.198	0.651
February	.....	1.21	0.603	1.03	0.867	0.355	1.09
March	.....	1.28	1.08	1.28	0.709	1.04	1.17
April	.....	0.966	0.543	1.21	0.766	0.719	1.16
May	.....	0.434	0.291	0.713	0.305	0.292	0.646
June	.....	0.241	0.208	0.336	0.214	0.180	0.310
July	.....	0.165	0.179	0.262	0.184	0.156	0.248
August	.....	0.141	0.151	0.205	0.161	0.134	0.200
September	0.099	0.113	0.121	0.164	0.134	0.115	0.161
October	0.100	0.100	0.113	0.136	0.133	0.117	0.140
November	0.121	0.129	0.125	0.137	0.140	0.115	0.143
December	0.245	0.429	0.234	0.637	0.214	0.348	0.410
Total	.....	5.72	4.35	6.57	4.82	3.77	6.33

Table 7--Average monthly discharge in C.F.S., Lufira River at Muadingusha
(Drainage-area = 5,380 square miles)

Month	1922	1923	1924	1925	1926
January	2293	1635	4065	1012	2940
February	2365	3140	3930	1781	5700
March	3480	4490	2940	3640	5000
April	2410	5650	3240	3610	5600
May	1104	3940	1580	1410	3415
June	773	1492	1170	845	1420
July	675	1090	965	674	1080
August	560	860	825	550	866
September	450	656	561	522	769
October	390	546	518	473	680
November	447	650	610	544	757
December	878	2580	883	1580	1835

Table 8--Runoff in inches on drainage-area, Lufira River at Muadingusha

(Drainage-area = 5,360 square miles)

Month	1922	1923	1924	1925	1926
January	0.494	0.352	0.877	0.218	0.633
February	0.457	0.609	0.792	0.346	1.11
March	0.750	0.968	0.633	0.783	1.08
April	0.503	1.18	0.673	0.731	1.17
May	0.238	0.851	0.341	0.302	0.738
June	0.161	0.312	0.244	0.176	0.294
July	0.145	0.236	0.208	0.145	0.232
August	0.121	0.185	0.178	0.119	0.187
September	0.094	0.137	0.117	0.109	0.160
October	0.084	0.118	0.112	0.117	0.164
November	0.093	0.135	0.127	0.113	0.158
December	0.189	0.557	0.190	0.336	0.396
Total	3.33	5.64	4.49	3.50	5.15

Sixteen current-meter measurements were made at the Tatalias gaging-station for discharges ranging from about 350 C.F.S. to 4,400 C.F.S. and ten current-meter measurements were made at the Muadingusha gaging-station for discharges ranging from about 600 C.F.S. to 4,900 C.F.S.

The foregoing data indicate what water-losses may be expected from areas covered with heavy growths of tropical grass and park-like timber located at an elevation of from 3,500 to 5,000 feet above sea-level, close to the equator and subject to a markedly seasonal rainfall and also subject to extensive natural stream-flow regulation by ground-water storage.

While the rainfall-data are too meager to furnish a basis for detailed estimates of water-losses, and the rainfall at higher elevations is probably greater than at the rainfall-stations, yet it is evident that the general rainfall over the drainage-basins of these streams is of the order of 50 inches, at least, per annum.

The mean runoff for the two streams for the periods covered by the records is as follows: Lualaba at N'Zilo gorge, 1921-1927, inclusive, 7.22 inches; Lufira at Muadingusha, 1922-1926, inclusive, 4.42 inches. These figures indicate that the water-losses from evaporative processes in this region must be at least 40 to 45 inches per year and as much more as the rainfall is greater than 50 inches.

There is rarely any evidence of an immediate response of stream-flow to rainfall even where the rainfall amounts to an inch or more per day. However, after a period of five or six days, in the case of the Lualaba River, a moderate increase in stream-flow takes place. This is evidently a response to accretion of ground-water.

The extremely moderate floods or maximum discharge is partly accountable to the fact that most of the rain falls in long successions of moderate amounts day by day and in part by the fact that all or nearly all the rain is absorbed by the soil. It is evident that an appreciable proportion of the infiltration reaches depths below the maximum from which it can be brought back to the surface by transpiration and evaporation. Some idea of the extent of the ground-water storage is revealed by the runoff records for the months May to September, inclusive, during which rain rarely occurs. For the Lualaba River the runoff during these months is seldom less than two inches on the drainage-basin, derived wholly from ground-water.

Attention is directed to the runoff Tables 3 and 8, where it will be noted that during the dry months, May to September, inclusive, there is surprisingly little variation in the runoff in different years. For example, for the Lualaba River the runoff in May ranged from a minimum of 0.605 to a maximum of 0.797 inch, and in August it ranged from a minimum of 0.288 to a maximum of 0.389 inch. It is evident that for these drainage-basins the rate of runoff at any time during the dry season, May to September, can be predicted in advance with a high degree of certainty.

There are no lakes within the drainage-basins of the upper Lualaba and Lufira rivers and no artificial regulation of any kind. The drainage-basins are largely covered with natural vegetation and the runoff is unaffected by artificial conditions, deforestation, cultivation of land, or drainage.

The soil covering these drainage-basins has been called laterite. This is the term generally applied to the porous soil formed by decomposition of certain rocks in tropical regions. The native rocks of the upper Lualaba River and Lufira River drainage-basins are sedimentary and consist of shale, sandstone, and limestone. At the head of N'Zilo gorge there is some conglomerate and the rock of the gorge itself is quartzite. The diamond-drill borings made at the Muadingusha dam-site on the Lufira River showed the rock there to be sandstone and shale. We have no definite information on the general depth of the soil cover in this region.

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NOTES ON VARIATION OF RUNOFF ON THE PACIFIC SLOPE

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The purpose of this paper is to discuss briefly some significant relations brought out by recent studies of runoff in the entire Pacific Coast area in Alaska, British Columbia, and the United States from Juneau to the Mexican border.

The study to date has involved the determination of the coefficient of variation of yearly runoff at 137 stream gaging-stations, 8 in Alaska, 19 in British Columbia, 36 in Washington, 46 in Oregon, and 28 in California. For California the number of records studied is less in proportion to total number of records of over ten years than in the case of the other States, while for Alaska all records of ten years or over have been used.

The coefficient of variation affords a valuable aid to the study of meteorological, hydrological, and other natural phenomena by statistical methods. It is a convenient expression for indicating the degree of dispersion of the terms of a series, such as a record of annual discharge of a stream. It is found by the formula

$$CV = \sqrt{\Sigma v^2/(n - 1)}$$

when CV is the coefficient of variation, v is the percentage of variation of each year from the mean, and n is the number of years of record.

The late Allen Hazen developed an analytical method for determining storage-requirement of streams for varying drafts, using two fundamental characteristics of a stream, its mean annual flow, and the CV. This method is described in "Water works practice," the manual of the American Water Works Association, and in the American Civil Engineer's Handbook (5th ed., pp. 1446-1452).

Richard G. Tyler, Dean of Engineering at the University of Washington, presented at the 1932 sectional meeting of the American Water Works Association a paper entitled "Storage requirements for northwestern streams," in which he sought to adapt Hazen's methods to streams in the north Pacific slope, and in which are tabulated the CV for 19 streams mostly in Washington, but including a few in adjacent states.

As a basis for such studies it is necessary to have records on as nearly as possible a comparable basis. Appropriate corrections should be made for storage, for depletion due to irrigation above the station, and for diversions out of the basin. Of the 137 records used in the present study, 27 have required correction for storage, 8 in Washington, 10 in Oregon, and 9 in California. No corrections have been made for either irrigation-depletion or diversions. Practically no records have been used for which such correction, if made, would have affected any yearly value by more than about five per cent.

The coefficient of variation was computed several years ago for a considerable number of western records. In a paper entitled "The probable variations in yearly runoff as determined from a study of California streams" (Trans. Am. Soc. C. E., v. 84, 191-257, 1921), L. Standish Hall has computed it for 35 California streams up to 1914 to 1917. The writer in certain studies made in 1922, while District Engineer for Oregon for the United States Geological Survey, computed but did not publish it for 14 records in Washington, averaging 15.6 years in length, and for 29 records in Oregon averaging 15.5 years. Some of these records have not been maintained to date, or if maintained it has not been found practicable to correct the later records so as to put them on a comparable basis with the earlier records; nevertheless, for 27 gaging-stations in the two states, two determinations of coefficient of variation have been made, the second for a period which in general is about 60 per cent longer than the first.

The records extending down to and including 1931 show a uniformly lower runoff and greater coefficient of variation than those for the earlier period. Thus, for 9 records in Washington the runoff decreased by an average of 6.6 per cent, while the CV increased from 0.232 to 0.264. In the case of Puyallup River this tendency is apparently reversed, but the Puyallup record ends with 1927. For 16 records in Oregon the original computations for an average of 17.9 years showed an average CV of 0.291; for the longer period the runoff averaged 11.4 less, while the CV was 0.357 or 0.066 greater.

Hall's studies of California records were made nearly 15 years ago and for some of the 35 stations which he used the records were available only up to the end of 1914. I have selected for comparative study 20 of these records. For an average period of 13.8 years Hall determined an average CV of 0.514; for the 30.2 years up to and including 1931 the average runoff decreased 18.4 per cent, the CV increased by 0.074 to 0.588. In no single instance was there an increase in runoff or a decrease in CV, although in the case of American and Kaweah rivers the coefficient remained the same.

The coefficient of variation shows a distinct tendency to increase southward as evidenced by the data given in Table 1.

Table 1--Average length of record, rate of runoff, and coefficient of variation

State	Years of record	Average	
		Second-feet per square mile	Coefficient of variation, CV
Alaska	12.8	14.0	0.120
British Columbia	17.2	2.70	0.220
Washington	21.1	4.06	0.241
Oregon	27.6	1.98	0.327
California	29.0	1.18	0.562

The coefficients of variation for all the stations in each of the five states have been grouped in order of magnitude and the percentage computed of the total number occurring between certain values. Thus, in Washington three or 8.3 per cent of all the coefficients are between 0.12 and 0.14, one or 2.8 per cent is between 0.14 and 0.16, 16 or 44.4 per cent are between 20 and 25. These values reduced to occurrences for each per cent of range have been plotted on Plate I to give frequency-curves, which show the following marked characteristics: Alaska--one very sharp peak at CV 0.12; British Columbia--two peaks at 0.13 and 0.21, the former higher; Washington--two peaks at 0.13 and 0.21, the latter much the higher; Oregon--a complex curve, most occurrences between 0.08 and 0.35, peak at 0.22; California--very widely distributed between 0.20 and 0.80, flat peak at 0.45 to 0.55; eastern United States--mostly between 0.16 and 0.30, one sharp peak at 0.22 (from data presented by Allen Hazen in Trans. Am. Soc. C. E., v. 84, 217, 1921).

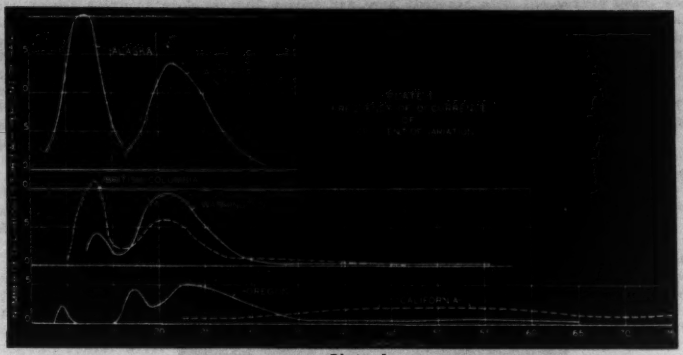


Plate I

For areas of low to moderate runoff and including the southern Sierra Nevada, the CV has a well-defined tendency to decrease with increase in rate of runoff. On Plate II the CV for about 40 such records has been plotted as coordinate with the average discharge per unit of drainage-area. For 17 California streams the plotted points give a fairly defined curve between CV = 0.46 for 1.6 second-feet per square mile to CV = 0.90 for 0.4 second-foot per square mile. For eastern Oregon the graph is defined by 16 points from CV = 0.33 for 0.8 second-foot per square mile to CV = 0.62 for 0.15 second-foot per square mile. For streams rising in the very humid area of Oregon, Washington, and British Columbia, the CV seems to bear no determinable relation to rate of runoff.

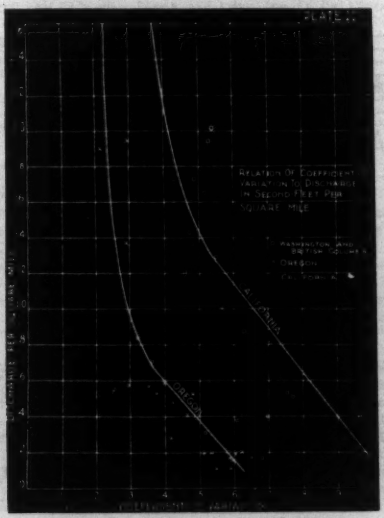


Plate II

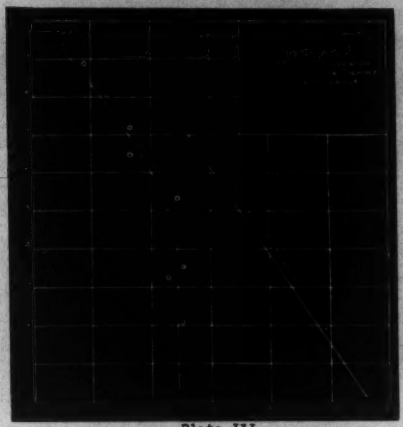


Plate III

The CV is relatively low for streams which derive a considerable portion of their runoff from springs. For two groups of stations, one in the Cascade Range in Oregon, and one in the upper portion of the Sacramento River Basin, the average discharge for

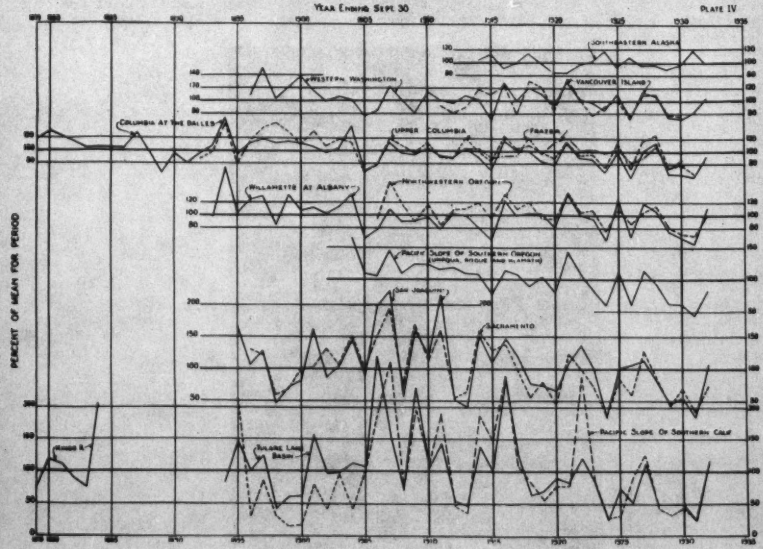


Plate IV--Yearly runoff in per cent of mean for selected stations and groups of stations

the lowest month of each year of record has been compared with the yearly mean, and this ratio plotted as a coordinate with the CV on Plate III. This average low month seems to be a fair index of runoff from springs and is readily obtainable. For the Oregon streams the CV increases with decreasing per cent of flow from springs down to a ratio of about 0.4, while for smaller ratios the CV seems to be more influenced by other factors. For the California streams the CV for the McCloud, Pit, and North Fork of Feather rivers--55 to 70 per cent spring-fed--is only about half of that for the American, which runs very low in summer, with the main Sacramento and the Feather plotting at intervening points on a straight line.

There is also a decided tendency for streams rising in glaciers and large ice fields to have a low CV, for example, Long River and Crater Creek in southeastern Alaska averaging 0.100, Columbia River at Golden 0.129 and at Trail 0.139, Puyallup River 0.127, Skagit River at Concrete 0.172, and Baker River 0.138.

Essentially as a by-product of this study, but of considerable interest nevertheless, particularly in view of the corrections made to obtain approximately natural flow, the yearly discharge ratios for the past 50 years have been plotted in graphic form for ready comparison on Plate IV. The following groups have been selected: Southeastern Alaska streams; four streams on Vancouver Island and 17 in western Washington; Fraser River at Hope, Columbia River at The Dalles, and eight tributaries of the upper Columbia; Williamette River at Albany, and four streams in the Cascade Range of northwestern Oregon; the Umpqua, Rogue, and Klamath (Link) rivers in southern Oregon; Sacramento River and two tributaries, and San Joaquin River and five tributaries; the four rivers tributary to the Tulare Lake Basin, and five in the Pacific Slope of southern California.

The similarity on the graphs in each group or in adjacent groups is generally quite marked. All except that for Alaska show the recent droughts, culminating in 1931, with a marked recovery in 1932. The southern Oregon streams show a declining tendency from 1904 to 1931. Occasionally the cycle is reversed as in 1906, which is low in the north and very high in the south, and 1898, 1899, and 1900, which are uniformly high north of the Columbia River and very low in California.

Federal Power Commission,
Washington, D. C.

STORM-FLOW PREDICTION

H. R. Leach, H. L. Cook, and R. E. Horton

Introduction-Synopsis

The object of this paper is to describe a method of predicting during the progress of a storm the total amount of surface-runoff which the storm will produce on a given drainage-basin. The measured runoff taking place from a small area is used as an index of the runoff to be expected from the same storm on a part or the whole of the main drainage-basin for which the prediction is made. The method herein described is, therefore, designated the "index-area method." This method was suggested by R. E. Horton. The details of its application have been worked out by H. R. Leach and H. L. Cook.

The value of reliable forecasts of storm-flows to all persons having to do with the control or economic use of stream-flow is self-evident. It arises from the possibility of preventing damage in the case of high floods and in making use of flow that might otherwise be wasted in the case of more moderate storm-flows. This paper deals primarily with forecasts made for the purpose of making more economical use of storm-flows. For example, a hydro-electric plant can increase its load in anticipation of a definte increase in flow and in so doing reduce the output of more expensive steam-power or relieve the loads on other interconnected hydro plants and conserve their supply of stored water. The flow released from a reservoir can be increased in order to distribute a replenishment from storm-flow over a longer period so as to prevent spillway waste, or if the storm is between the reservoir and power-plant, the release of storage can be stopped and the plant allowed to run on storm-flow.

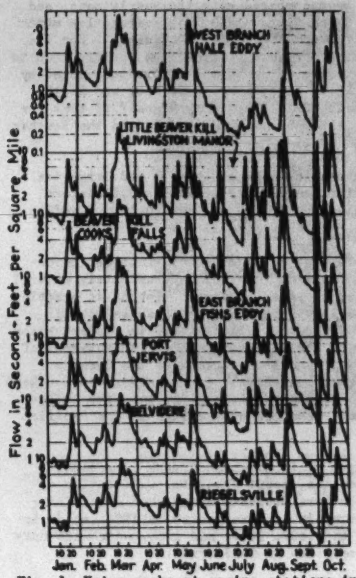


Fig. 1--Hydrographs at gaging-stations in Delaware River Basin, 1927

The index-area method

The method depends on the fact that there is usually a close correspondence between the form of hydrograph produced by a given storm on different streams within or subdivisions of a given drainage-basin. This fact is illustrated by Figure 1, showing yearly hydrographs at different gaging-stations within Delaware River drainage-basin. Some of the gaging-stations are on the main stream, some on small, some on large, tributaries, yet with scarcely an exception there is a close agreement in the runoff-characteristics for every rise or peak at every gaging-station. If differences of rainfall are taken into account, this correspondence of runoff-conditions in different parts of the same drainage-basin makes it possible to use observations of runoff from one or more small subdivisions of a drainage-basin for the purpose of estimating runoff which will take place from the entire drainage-basin. Most of the surface-runoff from a small index-area occurs during or within a short time after the end of the period of most intense rainfall. This may be a considerable time before the actual end of rain.

The promptness with which runoff may be determined for a small index-area is illustrated by records kept on La Grange Brook at

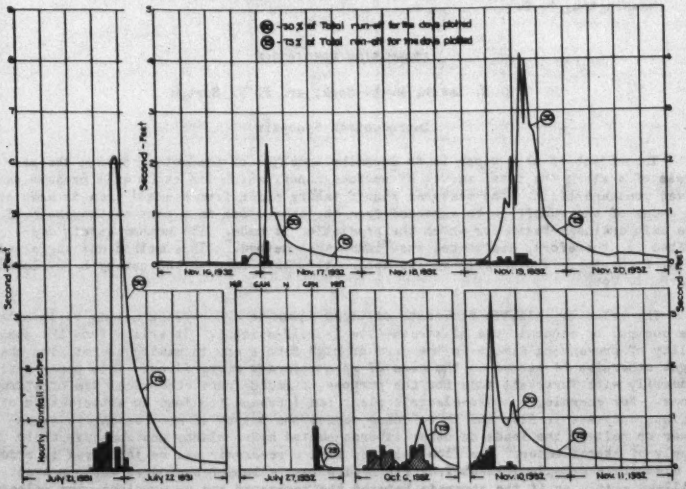


Fig. 2--Storm-flow hydrographs, La Grange Brook, near Voorheesville, New York

the Horton Hydrologic Laboratory, on an area of 36 acres. Figure 2 gives several hydrographs of storm-flow from this area. In moderate, summer storms, 75 per cent of the storm-flow had run off almost immediately following the cessation of rain. In the later fall storms about 50 per cent of the flood-flow had occurred by the end of the storm and 75 per cent from 8 to 12 hours later.

Owing to the existence of a large volume of water in transit in the stream-channel from remote parts of the drainage-basin, a large part of the surface-runoff from an extensive drainage-area is deferred until after rain ends, sometimes several days after. The increased runoff lag for large areas compared with the small index-area makes it possible to utilize the observed runoff from the latter for prediction-purposes at a sufficiently early date to give results which may be of considerable value in power-plant operation, especially in conjunction with the use of storage-reservoirs.

For power-production in conjunction with the operation of reservoirs the information most needful is the total storm-runoff. The replenishment of depleted storage and pondage is a question of the total flow available for refill and not of the rate at which the flow enters the reservoir. Information as to the time of occurrence or distribution of runoff during and after the storm is also furnished by the index-area method. The extension of this method to the determination and prediction of maximum discharge or peak runoff-rates is possible but will not here be undertaken. The underlying idea of this method resembles that of L. K. Sherman's unit-graph method of estimating runoff (L. K. Sherman, Stream-flow from rainfall by the unit-graph method, Eng. News-Rec., April 7, 1932, pp. 501-505) except that the unit graph here utilized for a particular storm is the actual runoff-graph of the same storm for the index-area or areas.

It is assumed that in applying the method, one or more index-stations will be established on suitable areas and operated for a period of time in conjunction with gagings and rainfall-records of the main stream, thus securing data to be used in establishing relationships between the runoff from the index-area or areas and the main area. When such relationships are established, the rainfall, rain-intensity, and runoff for each index-area will be recorded as it occurs and the runoff-relationship applied to determine the runoff to be expected from the sub-area to which a given index-area applies or to the total area.

In addition to index-stations it is necessary or desirable to have suitable rain-gages at different points on the drainage-basin, reports from which can be received by telephone or otherwise at the central office as the storm progresses. This makes possible an early comparison of total rainfall on the main area and that on the index-areas.

A typical situation is shown by the basin in Figure 3, in which R is the main station for which the prediction is to be made, and stations 1, 2, and 3 are index-area stations, representing, respectively, sub-areas A, B, and C of the drainage-basin. In the case of a storm on the basin a large part of the storm-flow from the three index-areas will be known almost as soon as the storm has passed over the basin and a forecaster can predict the runoff at R with considerable accuracy. Later observations from the index-area stations will increase the reliability of his prediction but a forecaster, basing his judgment on former experience, should be able to make his initial prediction with sufficient accuracy so that it will not require material change except, of course, where later storms superimposed upon the first storm, add increments to his initial prediction.

This is the method in outline. Details must be worked out according to conditions for each drainage-basin to which the method is applied.

Application of index-area method to Iowa River

The practical application of the method may be illustrated by the use of Ralston Creek drainage-basin, near Iowa City, Iowa, as an index-area for prediction of storm-runoff of Iowa River.

Iowa River has a length of 260 miles and a drainage-area of 3,230 square miles above Iowa City. It is a long, narrow basin, averaging about 20 miles in width. The

Fig. 3--Drainage-basin showing sub-areas, index-stations, and supplemental rainfall-stations

upper part consists of poorly drained, morainic glacial drift. The topography of the lower part is rolling except for the flat alluvial valley of the Iowa River. About two-thirds is cultivated, with the balance consisting of pasture and a small amount of woodland. The runoff averages 0.46 second-foot per square mile, with a maximum flood-flow of about 35,000 C.F.S.

Ralston Creek, a tributary of Iowa River at Iowa City, has a drainage-area of 3.0 square miles. The soil in the Ralston Creek drainage-basin is loess, the topography moderately rolling and about five per cent of the area is wooded, the balance being pasture or under cultivation. The extent of this area under cultivation remains nearly constant from year to year. While there is apparently ground-water in pockets and depressions, the drainage-basin as a whole is not underlain by a perennial water-table and all or nearly all the runoff resulting from summer storms is direct surface-runoff. The relative locations of Iowa River and Ralston Creek drainage-basins are shown on Figure 4.

A gaging-station with an automatic water-level recorder is maintained on Ralston Creek under the supervision of Dr. Floyd A. Nagler, Engineer-in-Charge, Iowa Institute of Hydraulic and Hydrologic Research. A tipping-bucket, rain-gage record is kept at the gaging-station and there are numerous rain-gages within the drainage-area. The observations are carried out in cooperation with the Bureau of Agricultural Engineering, United States Department of Agriculture. The authors are indebted to Dr. Nagler for copies of annual reports of the observations and other data used in connection with this study.

Storm-flow as used here is the runoff produced by a given storm over and above what the flow would have been had no storm occurred. It is the runoff above a base-flow consisting of ground-water flow and, in some cases, the remaining storm-runoff of a preceding storm.

The storm-flow of Ralston Creek is, as already noted, almost wholly surface-runoff. Iowa River, on the other hand, receives a considerable amount of ground-water. In order to compare the storm-runoff of the two drainage-basins in the same storms it is necessary to eliminate the ground-water flow--including water in transit in stream channels--from the Iowa River runoff. For this purpose a normal ground-water depletion curve, Figure 5, was prepared. This curve was obtained by superposing segments of hydrographs during periods of no rainfall sufficient to produce surface-runoff on Iowa River. The curve represents the runoff which would take place subsequent to a date when the stream is at a given stage if no rainfall occurred thereafter. It may be used for two purposes: (1) To determine the part of the flow during and following a storm which does not result from the storm, and (2) it may be used to determine the amount of storage available to supply the stream for any given time in the absence of rainfall. The volume of storage available between two different stream-stages is the area under the normal depletion-curve between ordinates corresponding to a given initial and final stage.

Fig. 4--Iowa River drainage-basin above Iowa City, Iowa

A typical illustration of storm-flow conditions for the Ralston Creek and Iowa River drainage-basins is shown in Figure 6 for the storm of August 3, 1928, in which A is the hydrograph based on hourly observations for Ralston Creek and B

Fig. 5--Depletion-curve of the Iowa River at Iowa City

is the hydrograph based on daily observations for Iowa River at Iowa City. The base flow derived from the normal depletion-curve of Iowa River during this runoff-period is shown by the dashed line aa . It will be noted that most of the runoff of Ralston Creek had taken place by noon of August 3; the peak-runoff of Iowa River occurred three days later. Nearly the entire storm-runoff of Iowa River occurred after August 3. Later on it will be shown that a prediction of the total runoff of Iowa River could have been made on the afternoon of August 3 that would have been substantially correct.

The relation of the storm-flow on Ralston Creek to that of Iowa River was determined from 16 general summer storms occurring in the period between 1925 and 1929. Storms were selected which produced surface-runoff on both streams. These storms are listed in column 2 of Table 1. In analyzing these storms the total rainfall on Ralston Creek drainage-basin was determined from several rain-geges maintained within that area. The mean rainfall on the drainage-basin of Iowa River for the same storm was determined from records taken at five rain-fall stations located as shown on Figure 4. Columns 3 and 4 of Table 1 show the measured runoff and rainfall on Ralston Creek. Column 6 represents the storm-runoff from Iowa River determined by deducting from the total runoff (including the amount still in storage at the end of the period) the depth of runoff corresponding to the area under the normal depletion-curve. There were wide variations in the amount of rainfall in the same storm on the index-area and on the Iowa River drainage-basin, so that there is only a moderately close relationship between the storm-runoff for the two areas. This relationship is shown by Diagram A, Figure 7. In order to take into account differences in rainfall, ratios of runoff to rainfall were computed for the two areas, as shown in Columns 5 and 8. The values of the runoff-ratios for Iowa River in terms of the runoff-ratios for Ralston Creek index-stations for the different storms are as shown on Figure 8.

This furnishes a relation-curve for converting runoff in a given storm on the index-area into runoff to be expected from a given known amount of rainfall on Iowa River drainage-basin. Applying this average relation-curve to the 16 storms analyzed, the estimated runoffs given in Columns 9, 10, and 11 are obtained. Using for a given storm the ratio y_1 to p_1, given in Column 5, the rainfall-runoff ratio for Iowa River was determined from Figure 8 as shown in Column 9. The rainfall on the Iowa River drainage-basin, as given in Column 7, was multiplied by this ratio, giving the estimated storm-runoff, as shown in Column 10. The difference between the estimated storm-runoff and the observed flood-runoff (Col. 10 minus Col. 6) appears in Column 11 of the Table. In other words, if the relation curve, Figure 8, had been available prior to 1925, predictions of the storm-runoff of Iowa River in these storms could have been made at or before the end of rainfall on the Ralston Creek index-area with the errors indicated by Column 11 of the Table.

The relation between the estimated and observed storm-runoff is shown by Diagram B of Figure 7. In general the agreement is sufficiently close to furnish valuable information for power-plant operation and other uses. Objection may, of course, be made to this comparison on the ground that the prediction is made for the same storms which were used in deriving the relation-curve. This is true but there appears to be no valid reason why equally good predictions will not be obtained for other storms as well.

Fig. 6--Flow of Ralston Creek and Iowa River, storm of August 3, 1928

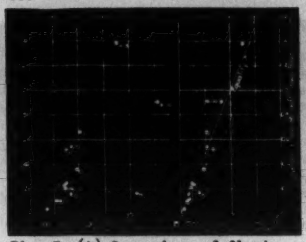


Fig. 7--(A) Comparison of flood-runoff of Iowa River Basin and Ralston Creek; (B) comparison of observed and estimated flood-runoff of Iowa River

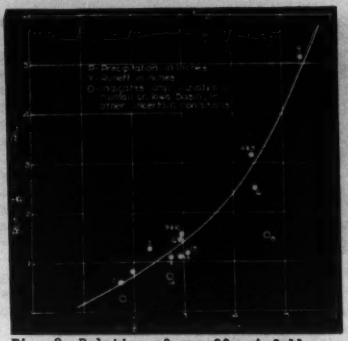


Fig. 8--Relation of runoff-rainfall ratios on Iowa River and Ralston Creek

Table 1--Storm-runoff and rainfall on Ralston Creek and Iowa River and comparison of estimated and observed runoff of Iowa River

No.	Date of beginning of flood	Ralston Creek, 3 square miles			Iowa River at Iowa City, 3230 square miles			Estimated storm-runoff of Iowa River		
		Flood runoff, y_1	Rain, P_1	Ratio, y_1/P_1	Flood runoff, Y	Rain[a] P	Y/P	Y'/P	Est'd runoff, Y'	Diff., (Y'-Y)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	1925	inches	inches		inches	inches			inches	inch
1	Sep. 8	0.39	2.20	0.177	0.04	1.49	0.027	0.060	0.09	+0.06[b]
	1926									
2	June 12	0.84	4.76	0.177	0.16	2.70	0.059	0.060	0.16	0
3	Sep. 1	1.04	4.46	0.233	0.66	5.16	0.128	0.100	0.52	-0.14
4-5	Sep. 19	1.78	4.06	0.439	1.38	4.35	0.317	0.29	1.26	-0.12
	1927									
6	May 8	0.77	1.73	0.445	0.52	2.09	0.248	0.30	0.63	+0.11
7	May 23	0.88	1.64	0.537	0.54	1.05	0.514	0.49	0.52	-0.02
8	June 20	2.13	4.55	0.468	0.17	1.11	0.153	0.345	0.38	+0.21[c]
9-10	Oct. 2,6	2.59	8.73	0.297	0.91	5.76	0.158	0.14	0.81	-0.10
	1928									
11	June 24	0.76	3.86	0.197	0.25	3.04	0.082	0.07	0.22	-0.03
12	July 18	0.71	2.58	0.275	0.24	2.19	0.110	0.124	0.27	+0.03
13	Aug. 3	0.96	3.25	0.295	0.36	3.29	0.109	0.138	0.46	+0.10
14	Aug. 23	0.57	2.09	0.273	0.11	1.56	0.070	0.122	0.19	+0.08[b]
	1929									
15	June 11	0.63	2.04	0.309	0.11	0.94	0.117	0.148	0.14	+0.03
16	June 30	0.73	2.48	0.294	0.21	1.43	0.147	0.138	0.20	-0.01

[a] Mean of rainfall at Ralston Creek, Belle Plaine, Marshalltown, Iowa Falls, and Belmond.

[b] Total Iowa River flood-flow uncertain.

[c] Highly variable rainfall on Iowa River Basin.

In this connection it may be noted that conditions are unfavorable for accurate runoff-prediction on the Iowa River drainage-basin: (1) Because only daily rainfall-data are available for the main drainage-area, whereas it is assumed that in applying this method hourly rainfall-observations would be available during periods of intense rain. (2) Owing to the length of the Basin and the fact that the direction of storms is generally across rather than along its axis, there are marked variations in the storm-flow from different sections of the Basin. Storms frequently occur on only part

of the basin, leaving the remainder untouched. Double flood-peaks are not uncommon. Under these circumstances, Ralston Creek, lying at the extreme lower end of the Basin, is not well located for the purpose of storm-flow prediction, and the fact that a fair relation between Ralston Creek and the Iowa River can be established brings out the possibilities of the index-area method.

In the case of a series of storms the forecast might be handled in the manner indicated in Table 2. Here the forecaster increases his predicted flow by adding to

Table 2--Predicted storm-flow of Iowa River, June 11-13, 1926

Date	Ralston Creek							Iowa River			
	Rain began	Time of reading	Rain, p	Total rain, Σp	Run-off, y	Total run-off, Σy	Ratio $\Sigma y/\Sigma p$	Rain, P	Total rain, ΣP	Ratio $Y'/\Sigma P$	Predicted runoff, Y'
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
			in.	in.	in.	in.		in.	in.		in.
June 11	8 p.m.										
12		8 a.m.	2.76	2.76	0.42	0.42	0.152	0.97	0.97	0.045	0.044
	3 p.m.										
		9 p.m.	1.15	3.91	0.13	0.55	0.141	0.56	1.53	0.040	0.061
	11 p.m.										
13		8 a.m.	0.63	4.54	0.22	0.77	0.169	1.14	2.67	0.056	0.150

the first storm-flow the runoff of subsequent storms and making new predictions based on the new total runoff. The total storm-runoff proved to be 0.17 inch but the preceding tabulation makes no allowance for the small amount of runoff on Ralston Creek subsequent to August 13, which an experienced forecaster would take into account. It is not contended, however, that accurate forecasts for a 3,000-square-mile drainage-area can be made from observations on a single index-area of three square miles located at one extremity of the basin. The whole point in presenting this example is to demonstrate the possibilities of the method by showing the good agreement that is obtained under such unfavorable circumstances.

Relations between index-area and main-area runoff

The method used for establishing the relationship between runoff on the index- and main-areas in the case of Ralston Creek and Iowa River by means of ratios follows along familiar lines of estimating rainfall- and runoff-relationships. This is not the only method and, in general, probably not the best method, of establishing relationship between an index-station and a larger area for the purpose of estimating storm-runoff. The fact that a close relationship exists between the runoff-ratios for the index-area and Iowa River depends upon certain, more fundamental, hydrologic factors. Storm-runoff, which is here under consideration, is very nearly equal to the part of the rain which falls at intensities exceeding the infiltration-capacity of the soil--in other words, it is the difference between total rainfall and infiltration.

Infiltration-capacity may be defined as the maximum rate at which the soil in a drainage-basin can absorb rainfall when the soil is in a given condition. The volume of rain which falls at intensities exceeding a given intensity corresponding to a given infiltration-capacity is designated "rainfall excess." For example, in a rainfall at the rate of one inch per hour lasting for one-half hour, the rainfall-excess for an infiltration-capacity of 1/2 inch per hour is 1/4 inch. For an infiltration-capacity of 0.3 inch per hour, the rainfall-excess in the same storm is 0.35 inch. The infiltration-capacity of a given drainage-basin in a given storm can readily be determined from a record of rain-intensity and runoff by plotting a diagram of rain-intensity, determining the rainfall-excess above different intensities, plotting a curve of rainfall-excess in terms of intensity and reading from this curve the value of the rain-intensity such that the rainfall-excess equals the surface-runoff. This has been done in the case of the 16 storms studied in connection with the Ralston Creek drainage-basin. The rainfall- and runoff-amounts and the infiltration-capacity in these storms are shown in the subjoined tabulation, Table 3.

Table 3--Infiltration-capacity of Ralston Creek drainage-basin in different storms, inches per hour

No.	Date	Rainfall	Infiltration-capacity, f
	1925	inches	inches/hour
1	Sep. 8	2.20	1.86
	1926		
2	June 12	4.76	1.62 - 0.22
3	Sep. 1	4.46	1.28
4-5	Sep. 19	4.06	0.55 - 0.46
	1927		
6	May 8	1.73	2.43
7	May 23	1.64	0.39
8	June 20	4.55	1.48 - 0.42
9-10	Oct. 2-6	8.73	0.30 - 0.20
	1928		
11	June 24	3.86	0.56
12	July 18	2.58	0.42 - 0.19
13	Aug. 3	3.25	0.40 - 0.08
14	Aug. 23	2.09	1.04
	1929		
15	June 11	2.04	1.71 - 0.96
16	June 30	2.48	2.50 - 0.36

In case more than one period of high rain-intensity occurred in the same storm, the values of f for the first and last periods are given. These figures show the rapid reduction of infiltration-capacity from a high to a low value as the result of rain. It will be noted that there was a wide variation in infiltration-capacity of the soil on this drainage-basin in different storms. It is apparently the variations in infiltration-capacity, together with variations in rain-intensity distribution, which in the main account for the wide variations which occur in the amount of surface-runoff produced by the same rainfall in different storms on the same area. For example, on Iowa River drainage-basin in three different storms the rainfalls in inches were 2.70, 2.09, and 2.19 with runoffs in inch of 0.16, 0.52, and 0.24 on June 12, 1926, May 8, 1927, and July 18, 1928, respectively. Here the runoff varied in the ratio of nearly 3 to 1 with the same rainfall. Such variations are a common occurrence. By the use of the index-area method, variations in runoff due to both these causes are automatically and completely taken into account so far as the index-area or areas are concerned. There are reasons for assuming that, in general, if not in all cases, both rain-intensity distribution and infiltration-capacity will differ from those for normal conditions for the entire area or sub-area to which a given index-station is applied in much the same way that they differ from normal conditions for the index-area. The ratios of y to p, used in deriving the relation-curve of Figure 8, while they appear in form as ordinary runoff-ratios, are, in reality, ratios of rainfall-excess to total precipitation and, as long as the ratio of rainfall-excess to total precipitation is either normal or departs from its normal value for a given storm in the same direction and to about the same degree both for the index-station and for the main area or sub-area, the use of such an average relation-curve will give good results.

If rain-intensity and infiltration-capacity do not vary alike on the index and main areas, a close relationship between the ratios p_e/p and P_e/P will not exist.

Cases will occur where the rain-intensity distribution for the sub-area and main area are dissimilar and even if the relation of infiltration-capacity of the two areas is normal, the ratios p_e/p and P_e/P will not be closely related. Such conditions may account for the larger departures from the normal curve shown by Storms 1, 8, and 14, on Figure 8.

Suppose that for such a storm, rain-intensity data are also available for a number of stations distributed over the main area and that from a study of previous storms the relation has been established between the infiltration-capacity for the sub-area and that for the main area. Having determined the infiltration-capacity of the sub-

area and therefrom the expected infiltration-capacity for the main area, the rainfall-excess or surface-runoff to be expected from the main area can at once be determined and in this determination the effect of departure of rainfall-intensity distribution from the normal on the main area is directly taken into account.

While variations in infiltration-capacity and their causes cannot be fully discussed here, the variations--which are large--are mainly due to two causes: (1) Drying and sun-checking of the soil and cultivation, which tend to produce a maximum infiltration-capacity; and (2) packing of the soil-surface by rain, washing of fine materials into soil-pores and other openings in the soil-surface, and swelling of colloid-material in the soil when moistened by previous rain--these factors tend to produce a minimum infiltration-capacity.

Now all these factors will operate, in general, in much the same manner on the entire drainage-basin, or at least on a given sub-area, as on the index-area, provided the soil-conditions of the index-area are representative of those on the sub-area or main area. A determination of infiltration-capacity for an index-area is therefore, at least, a good indicator of the infiltration-capacity pertaining to the larger areas.

Other refinements of the method are possible which cannot be detailed here. If a considerable portion of the area is under cultivation it may have an infiltration-capacity in excess of any rain-intensity likely to occur. The extent of such cultivated areas may be determined from time to time, their condition reported, and these areas deducted from the total and the remainder only used as representing the effective area from which surface-runoff will occur in a given storm.

Briefly, the apparent advantages of the rainfall-excess- or infiltration-method are: (1) The runoff-estimate is based on that part of the rain which actually produces surface-runoff, that is, the rainfall-excess; and (2) the marked effects of varying absorptive capacity of the soil are directly taken into account for each individual storm instead of being averaged, as in cases where runoff-coefficients or a normal runoff-rainfall relation-curve is used.

It is regretted that it has not been possible to establish runoff-relationships between Ralston Creek and Iowa River directly on the basis of rainfall-excess and infiltration-capacity, partly for want of adequate data of rain-intensity distribution. Attention is, however, called to the matter as a promising method of procedure in establishing the required relationships for storm-flow prediction from an index-area.

Selection of index-areas

The size of index-areas may range from a few acres to several square miles and on areas of these sizes the storm-flow is quickly concentrated and disposed of, so that within a period of a few hours following the cessation of the storm-rainfall, most of the runoff produced by the storm has been measured at the index-station.

In general, practical considerations will limit the number of index-area stations to two, three, or four. Assuming, for example, that three stations are to be established, these should be located to represent approximately the upper, middle, and lower thirds of the basin, not, however, basing these proportions on surface-area alone but also taking into consideration the relative amount of storm-flow contributed from different parts of the basin.

The index-area should be so selected if possible that its characteristics, particularly as regards infiltration-capacity, are representative of the area or sub-area to which it is applied. If, however, there is a wide diversity of conditions within a given area or sub-area, as, for example, where part of the area is forest or grass-land and part is under cultivation, it is desirable that the index-area should be representative of the more impervious portion of the larger area. In cases where a diversity of conditions is to be taken into account it may be advisable to establish artificial runoff-plats in conjunction with the index-stations. Such a plat, for example, may be 10 feet wide and 30 feet long and should be equipped with a tank and recording-gage or other means for measuring the surface-runoff The surface of such

plats may be cultivated, sown to grass or otherwise treated artificially to resemble a portion of the drainage-basin.

Promptness in getting complete observations to the forecaster is a primary consideration in establishing index-stations for storm-flow predictions. Quick results are facilitated by the use of small index-areas, which give rapid runoff in short periods of storm-flow. The size of the index-area is a matter of balancing the rapidity with which results are obtainable against the better representation of average conditions on the main drainage-basin which may be obtainable by the use of a larger index-area. The location and size of index-areas to be used is a matter of judgment and should be given careful study before selecting the area, as the value of the station increases with the length of its record and once established it should not be moved.

The selection of index-areas should preferably be made under the supervision of an engineer well versed in the principles of hydrology who has a broad experience in studying and analyzing rainfall and stream-flow data. Following the installation of the stations and the instructing of the observers he will receive observations until a sufficient number have been obtained from which to make a preliminary analysis and outline a tentative method.

The results of observation and experience in stream-flow prediction by the index-area method are cumulative and the method may be refined and its accuracy increased as the duration of the records available increases.

EQUIPMENT

The station equipment must serve two purposes: (1) Enable the observer to take readings quickly and easily, and (2) give complete data from which the observations can be studied and analyzed. Any one of several methods can be used to measure the flow but an automatic water-stage recorder is indispensable, storm-flows on small areas being of too short duration to place dependence on infrequent gage-readings.

A rain-gage is required and, while the standard 8-inch rain-gage will serve the first purpose, it is essential that intensity-records be obtained by a tipping-bucket or other type of recording rain-gage in order that the rainfall- and runoff-observations may be intelligently analyzed. Temperature-records are needed for the prediction of winter and spring runoff. Maximum and minimum thermometers should be installed and it is desirable to have a thermograph also, as it will give valuable information in interpreting results. Other meteorological equipment, although not essential, will add to the value of the station.

Supplemental stations should be equipped with ordinary 8-inch rain-gages, carefully located to give them adequate protection from wind-gusts. The snowboard-method should be used for measuring snowfall and if predictions of runoff from melting snow are to be made, a record of snow-depth and water-equivalent should be maintained at each supplemental station. Standard maximum and minimum thermometers should be installed and read, at least during the snow-melting season.

It is extremely desirable that records of ground-water level should be kept at the index-stations and at as many as possible of the supplemental stations, the readings being taken daily in wells where but little water is utilized from the well. Wells specially constructed for this purpose can be put down with a well auger in sand or clay soils, free from large stones, at little expense. Such records in conjunction with the normal depletion-curve derived from the hydrograph furnish the best possible basis for determining the amount of base-flow available at any given time.

RUNOFF FROM MELTING SNOW

The prediction of runoff from melting snow in midwinter warm spells is essentially the same as in fall storm-periods and the index-area method is applied in the same manner. The time-rate of runoff will be affected, however, by temporary detention of surface-runoff by freezing during the night and in subsequent sub-freezing periods.

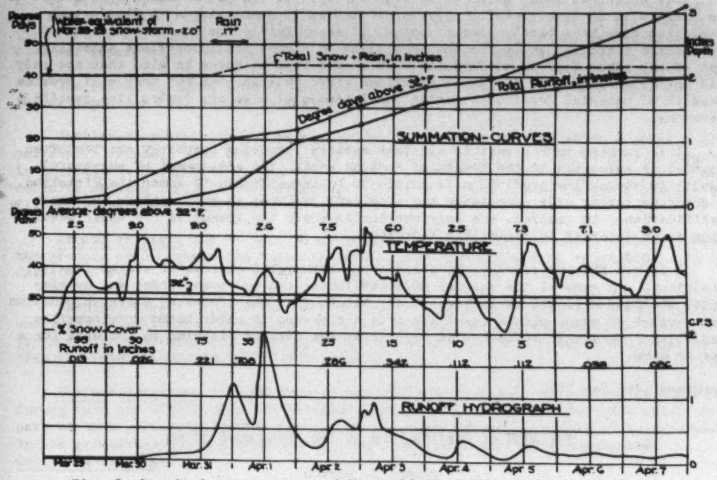


Fig. 9--Runoff from snowstorm of March 28-29, 1932, on La Grange Brook

In the period of general spring runoff, predictions are made chiefly for the purpose of forecasting flood-stages or the total flow available for reservoir replenishment. The necessity for quickly predicting the storm-runoff in order to make the most efficient use of the flow is diminished because of the high flows generally prevailing.

With regard to the refill of reservoirs and the prediction of spring flood-stages, the forecaster will know from his observations the total snowfall, the amount that has run off, the condition of ground-water and soil-moisture, and the available supply still in storage in the snow-cover. With these data he will be able to estimate the effect of a rise in temperature or a heavy rainstorm on the basin.

The phenomena of runoff from melting snow differs in many respects from rainstorm-runoff. Clyde (Geo. D. Clyde, Snow-melting characteristics, Bull. 231, Tech., Utah Experiment Station, Logan, Utah) found that the rate of melting was materially affected by temperature, whereas temperature had little effect on the drainage through the snow blanket to the ground surface except in cases of prolonged periods of sub-freezing temperatures. Temperature, however, does have a material effect on the run-off in transit over bare ground surfaces. Sub-freezing temperatures quickly arrest this flow and it is not released until the temperature rises above 32° F, after which the release is rapid. Our own observations indicate that this frequently causes the highest peak-flows in the melting period. Clyde emphasizes the importance of snow-density on the rate of melting but it appears that this is largely a measure of the result rather than a cause.

The high correlation between runoff from melting snow and excess temperature--temperatures in excess of 32° F--is shown by the summation-curves of temperature excess and runoff on Figure 9. This Figure shows the hourly temperature-excess and flow following an 18-inch snowstorm that occurred on La Grange Brook on March 28, extremely late in the season. The runoff amounted to approximately 0.09 inch per degree-day. Clyde found 0.091 inch per degree-day for field conditions on the Wasatch Plateau in Emery County, Utah, where the elevation averaged about 9,500 feet. In his laboratory experiments on snow-columns the melting ranged from 0.063 inch to 0.075 inch per degree-day. In an eight-day warm spell, February 17-24, 1933, we found only 0.03 inch per degree-day, which is probably accounted for by the fact that this period was followed by several days of sub-freezing temperatures that arrested the flow.

This paper has dealt principally with the application of the index-area method to the prediction of total runoff. Its possibilities in connection with flood-stage prediction have been barely touched upon. It seems fairly obvious that the method possesses a potential value for the prediction of storm- and flood-flows exceeding that of any other type of observation. It should also be borne in mind that not only will the establishing of index-area stations serve this purpose but they will provide a wealth of material for investigating the fundamental elements controlling runoff-phenomena.

It is perhaps unnecessary to add that matters involving hydrology are too often slighted or relegated to the domain of routine work. The attainment of successful results in storm-flow prediction is mostly to be accomplished if under the direction of some one having wide experience and excellent judgment in such matters and these qualifications, in general, are only attainable where the incentive for their acquisition is an interest in scientific hydrology.

It is not the purpose here to discuss the commercial aspects of stream-flow prediction. In general the expense of establishing and equipping index and supplemental stations will not be large. It may happen that the increased energy-production for a system of power-plants resulting from the saving of water based on storm-flow prediction in a single storm period will cover the cost of carrying on the work for a year or more.

Voorheesville, New York

THE RÔLE OF INFILTRATION IN THE HYDROLOGIC CYCLE

Robert E. Horton

Introduction--Definitions

For some years the author has used the term "infiltration" to describe the process involved where water soaks into or is absorbed by the soil. Absorption, imbibition, and percolation are often used in much the same sense. It seems better to confine the use of "percolation" to the free downward flow by gravity of water in the zone of aeration--a process for which a distinctive term is needed. "Absorption" includes the entrance of air as well as water, both liquid and vapor, into the soil (see Patten and Gallagher, Absorption of vapors and gases by soils, U.S. Dep. Agric., Bul. 51, Bur. Soils, Wash., 1908; also Charles H. Lee, On absorption and transpiration, Trans. Amer. Geophys. Union, 1932, pp. 288-298). "Infiltration" is limited to water in the liquid form and is more accurately descriptive of the physical processes by which rain enters the soil. "Water-penetration" is also sometimes used as if synonymous with infiltration. Its use should be restricted to the depth below soil-surface reached by the given surface infiltration.

"Infiltration-capacity" will be used to describe the maximum rate at which rain can be absorbed by a given soil when in a given condition. Infiltration is (a) the sole source of soil-moisture available to supply the transpiration stream and sustain the growth of vegetation, and (b) the sole source of ground-water supply of wells, springs, and streams.

The surface of a permeable soil acts like a diverting dam and head-gate in a stream, where the head-gate can be opened to a certain width only or closed so as to still leave a fixed opening. With varying rates of flow in the stream, all the flow is diverted up to the then capacity of the opening. Similarly, with varying rain-intensity, all of the rain is absorbed for intensities not exceeding the infiltration-capacity, while for excess rainfall there is a constant rate of absorption as long as the infiltration-capacity is unchanged. As in the case of the dam and head-gate, there is usually some pondage which remains to be disposed of after the supply to the stream is cut off, so in the case of infiltration, surface-detention remains after rain ends. Infiltration divides rainfall into two parts, which thereafter pursue different courses through the hydrologic cycle. One part goes via overland flow and stream-channels to the sea as surface-runoff; the other goes initially into the soil and thence through ground-water flow again to the stream or else is returned to the

air by evaporative processes. The soil therefore acts as a separating surface and the author believes that various hydrologic problems are simplified by starting at this surface and pursuing the subsequent course of each part of the rainfall as so divided, separately. This has not hitherto, in general, been undertaken.

The following terms require definition. (Quantities used in this paper are inches depth per hour unless otherwise stated.)

Infiltration-capacity may be defined as the maximum rate at which a given soil can absorb rainfall when the soil is in a specified condition. Infiltration-capacity, in general, is designated f. As subsequently shown, for a given soil there is a fairly definite maximum infiltration-capacity, designated f_g and a more definite minimum infiltration-capacity, designated f_c.

Ground-rainfall may be defined as the part of the rainfall which actually reaches the ground, or it equals the total rainfall minus interception by vegetation. It is designated P_g.

Rainfall-excess (P_e) is the part of the rainfall which falls at intensities exceeding the infiltration-capacity. For example, if the rain-intensity is 1.5 inches per hour for a 30-minute interval and the infiltration-capacity is 0.8 inch per hour, then the rainfall-excess is $0.7 \times 0.5 = 0.35$ inch.

Surface-detention is that part of the rain which remains on the ground-surface during rain and either runs off or is absorbed by infiltration after rain ends. A part of this surface-detention is usually contained in small pockets or depressions in the ground-surface and none of this runs off. This portion is designated detention-storage.

Field moisture-capacity (designated fmc or m_c) is used in the sense of the quantity of water which can be permanently retained in the soil in opposition to the downward pull of gravity. It may be expressed in per cent of dry weight or in inches depth for a given depth of soil.

Field moisture-deficiency (designated fmd or m_d) for any soil and time is the quantity of water, similarly expressed, which would be required to restore the soil moisture-content to field moisture-capacity.

The term ground-water accretion is used to describe the total quantity of water added to the water-table in any given time-interval. It is synonymous with the term re-charge as used in western United States and ultimate percolation as used in England.

Soil-moisture accretion is that part of infiltration which is retained in the zone of soil-moisture and which does not pass on downward to the water-table.

The storm-interval is the natural hydrologic time-unit. It may be defined as the interval from the beginning of a rain through the rain-period and the subsequent dry or rainless period to the beginning of the next subsequent rain-period.

Rise is used, for want of a better name, to define the period during and following rainfall from the time when the hydrograph first departs from the normal depletion-curve until it again becomes coincident with the normal depletion-curve. All of the surface-runoff due to the storm takes place in this interval. A rise consists of a period of increasing flow, which may result either from increased ground-water flow, from surface-runoff, or both. This culminates in the crest or peak of the rise, which is followed by a recession period.

Concordant flow is a condition of a stream such that if the rate of ground-water inflow to the stream remained unchanged, there would be no change in the stage of or rate of outflow from any given reach of the stream.

Normal depletion-curve

In the determination of total infiltration from runoff-records it is necessary to subdivide total runoff into two principal components: Ground-water flow and

surface-runoff. This may be accomplished by the use of a "normal depletion-curve." Consider a period of little or no rain. Stream-flow is then derived from storage. If there is no artificial regulation and no lakes or marshes on the drainage-basin, the stream-flow is derived either from ground-water or from waters in transit in stream-channels. At lower stages of the stream and when flood-waters are not passing downstream, the water in transit in stream-channels is itself derived from ground-water. For practical purposes and for the sake of brevity the flow of a stream at such times may be referred to as "ground-water flow."

After the passage of a flood or a rise due to surface-runoff, a stream settles down to what may be called a condition of concordant flow. The flow is variable in a hydraulic sense in that the same quantity does not pass each cross-section but the conditions are also such that if the inflow from ground-water remained unchanged there would be no change in depth or quantity of water stored in any reach of the stream.

A curve representing a segment of a hydrograph under conditions of concordant flow may be called a normal depletion-curve. It is also a time-discharge rate relation-curve. Since the area under the depletion-curve between two dates equals the total runoff and also equals the total draft from storage for the given period, it is easy to construct a second or storage-discharge rate relation-curve. If ground-water level-records are available this may be in the form of a ground-water level and discharge-rate curve, or virtually a rating curve for ground-water flow. For streams where the ground-water level underneath the drainage-basin is at a depth beyond the reach of direct abstraction by plants or vegetation, the normal depletion-curves in different years are often nearly identical throughout their common range within the limit of errors of observation and excluding the effects of barometric changes, etc., on ground-water flow.

The normal depletion-curves may differ to a considerable extent in different years or seasons in cases where there is a direct abstraction of ground-water from the water-table by vegetation or evaporation. Even in such cases the difference between summer season depletion-curves in different years is often so small that for practical purposes in separating ground-water and surface-runoff, an average normal depletion-curve can be used. [The author first noticed the characteristics of normal depletion-curves during a long drought which occurred in the eastern United States in the spring of 1903 and published depletion-curves for this drought-period in the Annual Report of the State Engineer and Surveyor of New York, 1903, v. 2, p. 16. Such curves were foreshadowed by the "storage curves" used by Vermeule (Geol. Sur. N.J., v. 3, Water supply, 1894).] Owing to interruption by rain and surface-runoff it is generally impossible to obtain a complete normal depletion-curve directly from a hydrograph. It can be shown that for a simple phreatic drainage-basin (with no direct abstraction from the water-table by transpiration or evaporation within the soil) the equation of the normal depletion-curve is

$$q = q_o e^{-ct}$$

where q is the ground-water flow-rate at the time t, and t is time elapsed subsequent to a date when the flow was q_o (Robert E. Horton, Discussion on yield of drainage-areas, J. New England Water Works Assn., v. 28, No. 4, Dec., 1914, pp. 538-539). [This particular formula was derived by the author from theoretical considerations in 1904 and applied to the depletion-curves of several streams. Its applicability to the springs of Cerilly was shown by Maillet (Eaux souterraines, 1905). In 1921 D. Halton Thomson (Trans. Inst. Water Eng.) showed that this type of expression accurately represents the law of decrease of ground-water levels in chalk regions of West Sussex, England, during rainless periods. Maillet states that this formula as applied to ground-water was first derived by him in 1903 and was independently derived by Boussinesq the same year.] Where a drainage-basin contains many phreatic sub-basins of different characteristics the normal depletion-curve for ground-water flow from the entire drainage-basin can in general be represented by an equation of the form

$$q = q_o e^{-ct^n}$$

in which n is a constant exponent. For a drainage-basin in which the gravitational capacity of the soil decreases proceeding downward, as is not uncommonly the case,

the normal depletion-curve can in general be represented by an equation similar to one or other of those above given but consisting of the sum of two exponential terms. By deriving the equation of the normal depletion-curve for a drainage-basin the curve can be extended so as to show the rate at which ground-water would be supplied to the stream: (a) During a drought-period of any duration and (b) during periods when surface-runoff is taking place if there was no coincident accretion to the ground-water table.

By shifting the normal depletion-curve horizontally across a hydrograph, segments of the hydrograph which coincide with the normal depletion-curve may be noted and these represent periods during which the runoff is derived entirely from ground-water flow. Connecting the points where the hydrograph departs from and rises above the normal depletion-curve, the accretion to ground-water and the ground-water flow during periods of surface-runoff can also be determined. In this way the ground-water runoff of the stream can be separated from the total runoff, thus making it possible by simple subtraction to determine the surface-runoff Y_s, since $Y_s = Y - Y_g$, where Y and Y_g are the total and ground-water runoff, respectively.

The many interesting and important properties of normal depletion-curves and their applications cannot be given in detail here. [Reference is made to the following papers: Samuel Hall, Stream-flow and percolation-water, Trans., Inst. Water Eng., v. 23, pp. 92-127, 1918; D. Halton Thomson, Hydrological conditions in the chalk at Compton, West Sussex, Trans., Inst. Water Eng., London, 1921. According to Gravelius (Flusskunde) the separation of ground-water from surface-runoff by drawing a line across the base of the hydrograph of a stream-rise has been practiced in France for more than 50 years. It seems necessary to point out that the method of separating ground-water flow from surface-runoff, used by Houk (Rainfall and runoff in the Miami Valley, Tech. Reports, Miami Conservancy Dist., Part 8, 1921) and by Meinzer and Stearns (W.S.P. 597-B) is incorrect and leads to underestimates of ground-water runoff, especially during wet months.] The author expects, however, to publish a full account of ground-water depletion-curves and their application in the near future.

Rain-intensity duration-curve

The rain-intensity duration-curve provides a good starting point for consideration of the rôle of infiltration in hydrology. Such a curve may be prepared either for an individual storm or for a season, a year, or other period in the same manner as the familiar runoff duration-curve. For a single storm, rain intensities for hourly or shorter intervals should be used and must be derived from the record of a recording rain-gage.

The lower diagram on Figure 1 shows the actual rain-intensity distribution in a typical summer storm on the drainage-basin of Relston Creek at Iowa City, Iowa. The total rainfall of 1.96 inches produced a runoff of 0.67 inch. There was no initial ground-water flow and the area under the runoff-curve extended to zero represents the total surface-runoff and is also equal, when suitable scale-factor is applied, to the portion of the rainfall shown by the shaded area. The shaded area on the rainfall-diagram represents that part of the rain which fell at intensities exceeding 0.55 inch per hour, which in turn was the infiltration-capacity of the drainage-basin during this storm. Inset A of Figure 1 shows the same rainfall plotted as a rainfall-intensity duration-diagram. If a horizontal line corresponding to some particular intensity is drawn across this diagram, the area between the intensity-curve and this line is the rainfall-excess for the given intensity. The line marked "rainfall-excess" on inset B of Figure 1 was derived in this way. From this diagram it is possible to read off directly the rainfall-excess corresponding to any given infiltration-rate. The total infiltration equals the total rainfall minus the rainfall excess, and a line of total infiltration has been added to Diagram B.

If the infiltration-capacity of a drainage-basin is known it is possible by an analysis of the rainfall-excess in individual storms, in the manner described, to determine, approximately at least, the surface-runoff which will take place directly from rainfall-data.

Also having given the runoff and the rain-intensity distribution it is possible to determine from these data the infiltration-capacity of a drainage-basin. For large areas it is, of course, necessary to determine the rainfall-excess for several stations.

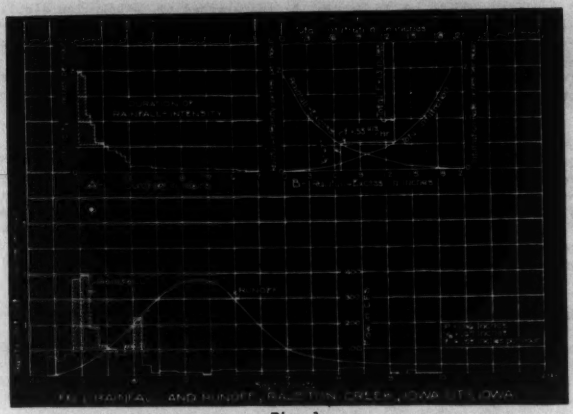


Fig. 1

Infiltration-capacity

Infiltration-capacity of a soil is closely related to but not necessarily and, in general, not actually identical with the transmission-capacity as used, for example, in Slichter's formula. The infiltration-capacity of a specific soil can be determined: (a) From laboratory experiments, using artificial rainfall; (b) from runoff-plat experiments, with natural rainfall; (c) from rainfall- and runoff-records for small drainage-basins with homogeneous soils; and (d) the average equivalent infiltration-capacity for a drainage-basin where the soil-type varies areally can be determined from runoff and rainfall-intensity records.

Few data have been published giving directly the infiltration-capacity of soils. Experimental and correlative researches for the determination of infiltration-capacity of soils have been carried out from time to time at the author's laboratory for a number of years. Only the briefest outline of the results can be given here. In the author's experiments, water was applied in a manner simulating rainfall to pans of soil of different types, under fully controlled conditions.

Various series of experiments by other investigators, made primarily for the determination of runoff-characteristics, have been analyzed for the determination of infiltration-capacity. These include laboratory experiments with artificial rainfall, made by Houk, by W. W. Horner, and by Duley and Hayes. Infiltration-capacities have also been determined from various series of runoff-plat experiments and from runoff-data for small drainage-basins, in particular, Ralston Creek, at the University of Iowa.

In discussing infiltration-capacity, two cases must be considered: (a) Natural soils, such as those of forest-covered areas, natural meadows, brushlands, and desert areas and, in general, all areas where the soil has remained fallow for a year or more; and (b) soils which have recently been cultivated.

Considering first the case of a natural soil, here the infiltration-capacity passes through a fairly definite cycle for each storm-interval. Starting with a maximum value when rain begins, the infiltration-capacity decreases rapidly at first as the result of the operation of some or all of the following processes: (1) Packing of the soil-surface by rain; (2) swelling of the soil, thus closing sun-checks and other openings; and (3) inwashing of fine materials to the soil-surface openings.

These effects are confined to a thin layer at the soil-surface. Infiltration-capacity during prolonged rain is, therefore, generally less than the gravitational transmission-capacity within the soil-mass. This is the principal reason why soils free to drain are seldom if ever fully saturated during rain, however intense or prolonged. Another reason is the necessity for escape of air as fast as the water enters the soil. This reduces the pore-space available for water within the soil.

The change from maximum to minimum infiltration-capacity during rain at once accounts for increased surface-runoff from initially wet soils or in a succession of storms, an effect commonly but erroneously attributed to saturation of the soil.

In the case of natural soils the infiltration-capacity may drop from one inch per hour or more at the beginning of rain to one-half inch per hour or less within an interval ranging commonly from one hour to two or three hours.

Thereafter, if the rain continues or the soil remains thoroughly wetted, a further slow decrease in infiltration-capacity takes place for a time, especially in the case of soils containing large percentages of colloidal material. When this colloidal readjustment becomes complete, the infiltration-capacity reaches a stable minimum value. This may not be materially less than the value attained shortly after rain begins.

After rain ends, restoration of the infiltration-capacity begins. Wind-action and differential temperatures close to the soil-surface aid in reopening the soil-pores, shrinkage of colloids takes place, perforations of earthworms and insects are restored, and the infiltration-capacity returns to its maximum value usually within a period of a day or less for sandy soils, although several days may be required for clays and fine-textured soils. Apparently the maximum and minimum infiltration-capacities for a given soil have fairly definite values at a given season of the year.

The range of variation of infiltration-capacity depends on the type of soil as well as its condition. Because of its large absorption-area per unit of surface-area and because of the temporary storage of rainfall in sun-checks, a sun-checked clay soil can initially absorb rain as fast as it falls. Similar conditions pertain in case of a newly plowed or cultivated field. In both instances the high initial infiltration-capacity is partly due to storage of water which is held in sun-checks, furrows, or small depressions until absorbed. Neglecting these exceptional cases, the range of infiltration-capacity between the maximum and minimum values is usually of the order of one inch in the case of loam soils, the range decreasing as the soil-texture becomes coarser. In the case of sandy soils which do not pack or sun-check and in which there are few earthworm or other artificial perforations, infiltration-capacity is apparently nearly constant or the range of variation is slight.

There is also a marked seasonal variation in infiltration-capacity. Apparently this is in part related to temperature but also in part results from the fact that earthworm and other perforations which freely admit water or permit the escape of air from the soil are present only during the summer season.

Table 1 shows the infiltration-capacity of the loess soil comprised in the drainage-basin of Ralston Creek at the University of Iowa, Iowa City, Iowa, derived from the analysis of 56 storms. In the case of storms designated "Class A" the soil-surface was initially dry, as there had been at least two preceding days without rain. In case of storms designated "Class B," rain of at least moderate intensity had occurred within an interval of not more than one day. It will be noted that the average infiltration-capacity during summer storms for initially dry soil was 1.25 inches per hour, while for Class B storms the average is 0.62 inch per hour or practically one-half as much. It will also be noted that the average infiltration-capacity in Class A storms varied in different years. The variation in different years is due in part to the effect of cultivation. About 20 per cent of the area was devoted to the growth of cereal crops; most of the remainder was grassland, including meadow and pasture.

An analysis was also made of ten winter storms which occurred during the months November to April. These gave an average infiltration-capacity of 0.12 inch per hour. This illustrates the marked difference in the ability of a soil to absorb rain under winter and summer conditions.

Table 1--Average values of infiltration-capacity f from analysis of individual storms, annual and eight-year means, Halston Creek drainage-basin, Iowa

Year	Class A		Class B		All storms	
	Average f	No. of storms	Average f	No. of storms	Average f	No. of storms
(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Summer storms, May-October, inclusive					
1925	1.55	3	0.53	2	1.14	5
1926	0.98	4	0.86	3	0.93	7
1927	1.43	3	0.28	5	0.71	8
1928	0.98	6	0.36	4	0.74	10
1929	1.65	3	0.97	3	1.31	6
1930	1.57	3	0.44	1	1.29	4
1931	1.07	2	1.92	1	1.35	3
1932	1.09	3			1.09	3
Average[a] 1925-1932, inclusive	1.25	27	0.62	19	0.99	46
	Winter storms, November-April, inclusive					
Average[a] 1925-1932, inclusive	....	..	....	..	0.12	10
	All storms					
Average[a] 1925-1932, inclusive	....	..	....	..	0.84	56

[a] Average of all storms--not average of yearly means.

Table 2--Summary of mean monthly values of infiltration-capacity, Halston Creek at Iowa City, Iowa

Month	Average values of f, inches per hour					
	Class A		Class B		All storms	
	f	No. of values	f	No. of values	f	No. of values
(1)	(2)	(3)	(4)	(5)	(6)	(7)
February	0.17	2	....	..	0.17	2
March	0.12	3	0.03	1	0.10	4
April	0.12	1	0.10	1	0.11	2
May	1.30	3	0.24	2	0.87	5
June	1.57	9	0.81	8	1.21	17
July	1.36	4	0.32	3	0.91	7
August	0.75	5	0.47	3	0.65	8
September	1.11	6	1.92	1	1.23	7
October	....	..	0.25	2	0.25	2
November	0.11	2	....	..	0.11	2
All values	....	..	....	..	0.84	56

Note--Class A: f for storms following two or more rainless days.
Class B: f for storms following one or less than one rainless day.

Seasonal effects, also the effect of cultivation, are further revealed by the data given in Table 2, which shows the average infiltration-capacity for storms occurring in different months of the year. For Class A storms, which represent approximately maximum infiltration-capacity, the value of f is of the same order for the months May, June, July, and September, but drops to a lower value in August, in which month tillage-operations on farms are generally at a minimum, as the season of corn-cultivation is over and the sowing of fall grain has not begun.

The other experimental data above referred to give results of the same general character. It is expected that these data will be published in full in the near future.

In view of the large variations of infiltration-capacity, even for the same soil when in different conditions, the question naturally arises as to the practicability of using infiltration-capacity as an independent variable in hydrologic studies. As already noted, infiltration-capacity changes rather quickly from its maximum to its minimum value during heavy rain, and after a rain its maximum value is restored, usually before the next succeeding heavy rain.

Actual variations in infiltration-capacity are not as great as they appear to be. Owing to the method of calculation of f, especially for large areas involving a deduction for ground-water, errors in the determination of either the rainfall or runoff may combine so as to produce a considerably greater error in the calculated infiltration-capacity.

The data thus far analyzed indicate that if there has been no recent rain, f is close to its maximum value during short intense storms of the summer thunder-storm type. This would be true, for example, for storms of less than one hour total duration of rainfall. For longer storms of the same type the value of f is about the average of the maximum and minimum values. For long storms of the cyclonic type and for all storms where there has been at least a moderate fall of rain within one day preceding, the value of f is close to the minimum value. In other words, if two heavy rains occur not more than a day apart, the ground being dry antecedent to the first rain, and if both rains are of short duration, the value of f will be close to the maximum value for the first rain and close to the minimum value for the second rain. If the maximum and minimum infiltration-capacities of the soil are known, a study of the rainfall-record will usually show the value of f applicable to a given storm.

A simple method of determining the range and approximate values of f for a small drainage-area consists in noting the intensities of the heaviest rains which do not produce surface-runoff--this will indicate f_c; and also the lightest rains which produce surface-runoff--this will indicate f_0.

Relation of infiltration to runoff

There are three ways of viewing runoff:

(1) As a fraction or percentage of rainfall. This is the usual concept when applied to average conditions. The average runoff can be determined by multiplying the rainfall by the ratio of runoff to rainfall or runoff-coefficient. There is, however, only an indirect relation between the average runoff-coefficient for permeable areas and the runoff-coefficient for particular storms. The average runoff may include a large percentage of ground-water flow, while runoff for an individual storm is mainly or wholly surface-runoff. Since surface-runoff is approximately equal to the rainfall-excess, and this is zero for rain-intensities less than the infiltration-capacity, it follows that the runoff-coefficient is not a constant, neither is it directly a function of the amount of rainfall. It is a direct function of the rainfall-excess intensity for rains of sufficient intensity to produce a rainfall-excess.

(2) Runoff may be considered as the difference between rainfall and water-losses. The water-losses include interception, transpiration, and evaporation from the soil. Runoff is the residuum left after these evaporative processes have taken their toll. This is the basis of the water-loss method of estimating runoff, largely used in England. It directly reflects the effect of the physical processes involved but makes no distinction between ground-water and surface-runoff and does not directly take storage-effects into account. It is therefore, applicable primarily to average conditions and not to individual storms.

(3) The infiltration-theory—Runoff from a permeable area generally consists of two parts: (a) Surface-runoff; (b) ground-water runoff. Neglecting interception by vegetation, surface-runoff is that part of the rainfall which is not absorbed by the soil by infiltration. If the soil has an infiltration-capacity f, expressed in inches depth absorbed per hour, then when the rain-intensity i is less than f the rain is all absorbed and there is no surface-runoff. It may be said as a first approximation that if i is greater than f, surface-runoff will occur at the rate (i-f).

Many attempts have been made to correlate annual seasonal or monthly runoff with rainfall-amount, or with rainfall-amount and evaporation or temperature, it being assumed that at a given locality temperature is the principal independent variable controlling evaporation-rate. The results have sometimes been expressed in terms of a method for computing runoff or extending runoff-records, such as the methods of Vermeule and Meyer. More often they have been expressed as runoff-formulas, of which there are many. Neither of these methods of procedure has met with any marked success.

An analysis of the relation of runoff for the summer season, May to October, inclusive, to rainfall, evaporation, and to rainfall and evaporation together, has been made for West Branch Delaware River for the 25-year period, 1904-29, for the purpose of determining the degree of correlation existing between these quantities. Briefly stated, the results indicate that the best which can possibly be done, even where the coefficients and relationships are derived directly from a long runoff-record, is to duplicate the record for individual seasons with an average error of about ten per cent but with much larger actual errors in the estimated runoff in individual seasons.

The imperfect correlation between total rainfall and evaporation, on the one hand, and runoff, on the other hand, is illustrated by Table 3, showing various data for West Branch Delaware River for the summer season, May to October, inclusive. The ground-water flow was determined by the use of a normal depletion-curve and the total runoff separated into its two elements: Ground-water runoff (Y_g), Column 4, and surface-runoff (Y_s), Column 5. Column 6 shows the ratio of seasonal evaporative capacity computed by the author's formula (Robert E. Horton, A new evaporation formula developed, Eng. News-Rec., Apr. 26, 1917, pp. 196-199). The apparent water losses, L', Column 7, represent the difference between rainfall and total runoff, without correction for gain or loss of storage. It will be noted that there are large differences in total runoff and surface-runoff, particularly the latter, in different years having approximately the same rainfall. For example, in 1909 we have P = 15.59, Y = 6.76, and Y_g = 3.42, while for 1913 we have P = 16.20, Y = 2.40, and Y_g = 0.94. These differences are not wholly accountable to variations in evaporation. While in most years excessive evaporation is accompanied by water-losses larger than the normal, this is not always true and, in any event, departures of evaporation from the normal are usually small compared with variations in either total or surface-runoff with the same amount of rainfall.

The author has long felt that there was some independent variable or variables other than total rainfall and evaporation-rate which should be taken into account. It will be noted that the infiltration-theory of runoff includes two new variables, namely, rainfall-excess and infiltration-capacity. Just how far the introduction of these new variables will serve to bridge the gap between observed and computed runoff remains to be determined. In accordance with this theory, total runoff consists of two parts:

(1) Surface-runoff, which is dependent on rainfall-amount, rain-intensity, and infiltration-capacity and is practically independent of evaporation-rate.

(2) Ground-water runoff. This is dependent on (a) total infiltration and hence indirectly on the same factors which control surface-runoff and is also dependent on (b) vegetational activity and evaporation, which in part determine the water losses, and on (c) the complex interrelations between infiltration-capacity, field moisture-capacity, vegetational activity, and accretion to the water-table. These relationships will be subsequently discussed.

Referring again to Table 3, Column 9 gives the ratio of the apparent water-losses to total infiltration. Attention is particularly directed to the relative constancy of this ratio. West Branch Delaware River drainage-basin is in a large de-

TABLE 3 - SEASONAL RAINFALL, RUNOFF AND WATER-LOSSES
WEST BRANCH OF DELAWARE RIVER AT HANCOCK AND HALE EDDY, NY
SUMMER SEASON - MAY TO OCTOBER INCL.
(All quantities except ratios are in inches Depth)

Year	P	Y	Y_g	Y_s	E_r	L'	F = P-Y_s	L'/F	f (a)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1905	23.29	6.06	2.97	3.09	0.982	17.23	20.20	0.853	0.86
06	23.08	7.11	4.21	2.90	1.01	15.97	20.18	.791	.79
07	20.30	6.83	3.98	2.85	0.928	13.47	17.45	.772	.96
08	16.71	5.32	2.95	2.37	1.12	11.39	14.34	.794	.80
09	15.59	6.78	3.36	3.42	1.05	8.81	12.17	.724	.34
1910	15.66	4.56	2.90	1.66	1.13	11.10	14.00	.793	.68
11	20.85	5.42	3.09	2.33	1.06	15.23	18.32	.831	1.05
12	18.71	4.43	3.10	1.33	1.04	14.28	17.38	.822	1.09
13	18.20	3.40	1.46	0.94	1.08	13.80	15.26	.904	1.03
14	20.90	5.67	3.55	2.12	1.04	15.23	18.78	.811	.68
1915	24.90	8.89	5.12	3.45	0.967	16.01	21.45	.746	1.14
16	23.19	7.87	5.68	2.19	1.08	18.32	21.00	.730	1.14
17	32.14	13.41	7.46	5.95	0.953	18.73	26.19	.715	.72
18	28.60	8.62	6.40	2.22	1.08	19.98	26.38	.758	.82
19	21.18	5.25	4.00	1.25	1.00	15.93	19.93	.799	1.16
1920	27.40	8.89	5.94	2.95	1.00	18.51	24.45	.757	1.10
21	23.18	4.69	3.68	1.01	1.11	18.49	22.17	.834	.73
22	26.03	8.28	5.35	2.93	1.01	17.75	23.10	.768	1.18
23	21.85	5.08	3.17	1.91	1.00	16.77	19.94	.841	1.00
24	24.53	10.40	5.46	4.94	0.835	14.13	19.59	.721	.62
1925	23.02	8.14	4.82	3.32	0.852	14.88	19.70	.755	.82
26	20.37	5.88	3.78	2.10	0.960	14.49	18.27	.793	1.00
27	26.69	11.56	5.39	6.17	0.812	15.13	20.52	.737	.82
28	25.35	13.06	7.54	5.51	0.880	12.29	19.84	.619	.63
1929	22.32	7.18	4.96	2.22	1.01	15.21	20.17	.754	1.20
Mean	22.48	7.27	4.42	2.85		15.20	19.63	0.777	0.90

(a) This is apparent infiltration-capacity in inches per day as deduced from daily rainfall-records. The actual infiltration-capacity is greater in the ratio of 24 to the number of hours per day of rainfall-excess duration.

gree covered with natural forest vegetation. The meaning of the constancy of this ratio seems to be that the natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil-moisture supplied by infiltration. The constancy of this ratio also suggests its utility as a factor for use in estimating water-losses from drainage-areas and, furthermore, it is apparent that the total infiltration represents the maximum amount of available or "effective rainfall" in relation to the growth of vegetation.

Phenomena of a stream-rise

The segment of a hydrograph from the end of a period of concordant flow when a rise begins and continuing through to the beginning of the next period of concordant flow may be designated a "rise." In reality, of course, it involves both a rise and a recession. A rise of a perennial stream begins as a result of rain of an intensity exceeding the infiltration-capacity f.

It can be shown that on a permeable drainage-area direct surface-runoff to the stream after rain ends takes place only from a restricted belt bordering the stream. From portions of the drainage-basin more remote from streams all of the overland flow or water in transit as surface-detention when rain ends enters the soil as infiltration and none of it reaches the stream.

As a result of this condition, direct surface-runoff into stream-channels ends very shortly after the end of the last period of rain-intensity exceeding infiltration-capacity. There is thereafter an interval of variable flow, its duration ranging from a few hours for very small areas to many days for large areas, after which the stream settles down again to a condition of concordant or nearly concordant flow. The flow is then represented by the normal depletion-curve. This continues until the beginning of the next rise. A hydrograph consists of a succession of alternating rises and intervals of concordant flow or flow derived from normal depletion of storage.

Fig. 2

Ground-water flow, of course, continues during the interval of the rise and follows the normal depletion-curve unless or until accretion to the water-table takes place. After accretion ends, ground-water flow in accordance with the normal depletion-curve is resumed, though perhaps at a higher level. Accretion to the water-table does not, however, occur during a rise unless the infiltration is in excess of field moisture-deficiency between the water-table and the soil-surface. These principles make it possible to classify rises appearing on a hydrograph in terms of rain-intensity, infiltration-capacity, and field moisture-deficiency.

The author's classification of rises is shown on Figure 2.

Type 0 is so designated because nothing happens as far as the stream is concerned. For this type the rain-intensity is less than the infiltration-capacity. There is, therefore, no surface-runoff. The total infiltration is less than the field moisture-deficiency and there is, therefore, no accretion to ground-water. The normal depletion-curve continues its downward course uninterrupted. There is, therefore, no rise in the stream. These phenomena are characteristic of light rains occurring during generally dry weather, particularly after long droughts when the soil has the maximum infiltration-capacity f_c. Type 0 is, however, something more than a gesture since soil moisture-accretion takes place. Soil moisture-accretion effects are cumulative and the occurrence of conditions of Type 0 may hasten the time when a real rise in the stream will occur.

Type 1--Again the rain-intensity is less than infiltration-capacity and no surface-runoff occurs. The total infiltration is greater than the field moisture-deficiency and some accretion to the water-table takes place, accompanied either by an increase in ground-water flow or a slowing down of the ground-water depletion-rate. These small irregularities in a hydrograph look like the effects of observational errors or barometric changes but they frequently result from rain. They are typical effects of light rain in the spring and of somewhat heavier rain of low intensity in the summer and fall.

Three different cases occur under Type 1, as shown on the diagram. In each case accretion to the water-table takes place during the interval denoted by mn. Normal ground-water depletion interrupted at m is resumed at n, while n' shows the corresponding stage had there been no ground-water accretion. In case (a) the rate of accretion is less than the rate of normal ground-water depletion. The depletion, therefore, continues but at a reduced rate. In case (b) the accretion and depletion rates are equal and the ground-water flow-rate remains constant for a time. In case (c) the rate of ground-water accretion exceeds the rate of normal depletion and there is a rise of the water-table and an increase in the ground-water outflow-rate.

Type 2--Here the rain-intensity exceeds the infiltration-capacity and surface-runoff occurs, but the total infiltration is less than the initial field moisture-deficiency and there is no accretion to the ground-water and hence no change in ground-water flow. The normal depletion continues during the rise and the ground-water regimen is resumed at n. The stream falls after the rise to a lower stage than pertained when the rise began. This is a growing season or midsummer type and commonly occurs when the field moisture-deficiency is large enough so that the field moisture-capacity is not fully restored by infiltration. Such rises are typical of the effect of short, sharp showers of the thunder-storm type.

Type 3--Again the rain-intensity exceeds the infiltration-capacity and surface-runoff occurs. In this type of rise, the total infiltration exceeds the field moisture-deficiency and accretion to the water-table takes place. The point n at which the rise ends is the point at which the recession-side on of the discharge-graph coincides with the normal depletion-curve.

There are three cases under Type 3 identical with those for Type 1-rises and dependent on the rate of ground-water accretion. Normal depletion-flow is resumed at the end of a rise of Type 3 at a higher stage than for a rise of Type 2, other things equal, but the stage at the end of the rise may or may not be higher than the initial stage. In cases (a) or (b), Type 3, the stage at which the normal depletion-flow is resumed will not be higher than the initial stage; in case (c) it will be higher. Whether a given rise is of Type 2 or Type 3 can be determined by extending the normal depletion-curve underneath the rise. If the recession-side of the graph returns to this curve as extended, the rise is of Type 2. If the normal depletion-curve at the end of the rise is at a higher level than the extended curve under the graph, the rise is of Type 3.

Compound rises occur where, as the result of a second intense rainfall, a second rise begins before the completion of the recession-phase of the first rise. There are, however, only three fundamental cases: Types 1, 2, and 3, as may readily be seen. A compound rise may, of course, be decidedly complex since any of the three types may be partly superposed on any other. This gives six cases for a compound rise, Type 1 on 2, 1 on 3, 2 on 3, 3 on 2, 3 on 1, and 2 on 1. Also each of the three types may succeed itself.

As regards its relation to ground-water accretion, a compound rise may always be resolved into one of the three fundamental types, since a rise of any one of these types always involves a reduction in field moisture-deficiency. A storm which produces a rise of a given type will, if compounded with a second rise, generally produce a compound rise of an order equal to or higher than that of either of its two components. Thus a rise of Types 1 and 2 combined will generally be of Type 3.

It may be noted that in order to bring out the various relationships described on a hydrograph a fairly open time-scale is required, say one inch equals five or ten days, together with not too small a discharge-scale.

Classification of stream-rises in the manner above described not only affords a definite basis for separation of ground-water flow from surface-runoff on a hydrograph but it affords a convenient starting point for determining what is going on within the non-saturated zone of the soil during and following rain.

Interrelations of infiltration, vegetation, soil-moisture, and ground-water

There are four hydrologic factors which limit and determine the adaptability of the soil of a given region to the growth of vegetation: (1) Rainfall-amount, duration, intensity, and seasonal distribution; (2) infiltration-capacity of the soil; (3) field moisture-capacity of the soil; and (4) depth to water-table, if one exists.

Infiltration-capacity limits the amount of water which can enter the soil. The excess is rejected as surface-runoff. The field moisture-capacity limits the part of the infiltration that can be retained in the non-saturated zone of the soil and is available to supply vegetation therefrom. If at a given time when infiltration occurs, there is a certain aggregate field moisture-deficiency, measured in inches depth of water, the excess of infiltration over field moisture-deficiency, if any, is rejected and percolates downward to the water-table. In general, the part of the ground-rainfall which remains in the soil available to supply soil-moisture requirements is that which remains after the rejection (1) of rainfall-excess at the soil-surface and (2) of excess of infiltration over field moisture-deficiency within the soil.

Depth to ground-water operates in three ways: (a) The water-table if too near the surface inhibits the growth of mesophytic vegetation, although hydrophytic plants may thrive, as on swampy areas; (b) if within the reach of plant-roots, the water-table may provide an important and even the larger part of the moisture-supply used by vegetation; and (c) if at a depth below the reach of plant-roots and evaporative uplift, the presence of a water-table has no effect on vegetation.

There is a close interrelation between infiltration-capacity, field moisture-capacity, and depth to water-table which does not seem to have been pointed out.

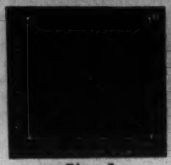


Fig. 3

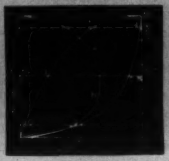


Fig. 4

Fig. 5

Fig. 3--Relation infiltration-capacity and field moisture-capacity to soil-texture (schematic)

Fig. 4--Infiltration oab and accretion to water-table oob, per cent of total (schematic)

Fig. 5--Relative ability of soils to support vegetation with and without a water-table (schematic)

Infiltration-capacity and field moisture-capacity are in a large measure complementary functions of soil-texture, the former increasing, the latter decreasing as one proceeds along the scale of soil-texture from clay and silt to sand and gravel. This fact and some of its consequences are illustrated by Figure 3. The base-scale oa represents soil-texture. The diagonal lines ob and ac may be taken to represent infiltration-capacity and field moisture-capacity, respectively.

For fine soil-textures near the left-hand end of the texture-scale, the infiltration-capacity f is small and the field moisture-capacity fmc is large. Plants may suffer because not enough water enters the soil to support luxuriant growth. For these conditions also there is a large rejection of rainfall at the surface and but little rejection within the soil, so that the final residuum available to supply the water-table is small; hence ground-water accretion is limited and a perennial water-table may not exist.

For coarse-textured soils, corresponding to the right-hand portion of the texture-scale, f is large and fmc is small. There is little surface-rejection of water but a large rejection of infiltration within the soil, so that, again, plants may suffer for want of soil-moisture, but there is abundant accretion of moisture to the water-table and ground-water supplies from such soils are generally plentiful.

In the central portion of the diagram there is both a moderately large infiltration-capacity and field moisture-capacity, a condition most favorable to plant-growth, bearing in mind that rain occurs in quanta, not continuously, while the demands of the plant for moisture are incessant and if the moisture-supply is interrupted, wilting, retarded growth, and perhaps death of the plant results.

It is not to be assumed that the relations of infiltration-capacity and field moisture-capacity to soil-texture are actually linear, as indicated by the lines oa and bc. Quite certainly these quantities are not linear functions of the average size of the soil-grains. This, however, does not affect the validity of the diagram for the purpose for which it is here used.

For a given rainfall-régime, as infiltration-capacity increases, the total infiltration increases, at first rapidly, then more slowly as the maximum rain-intensity is approached. This is illustrated by the line oab, Figure 4. The base-scale in this case shows infiltration expressed as a percentage of total rainfall.

As the field moisture-capacity of the soil decreases, that is, as the infiltration-capacity increases, the proportion of infiltration which is rejected within the soil increases. The total rejection within the soil equals the total accretion to the water-table and can be determined from ground-water flow and runoff-records. The relations of the accretion to the water-table or total rejection of moisture within the soil to total infiltration and infiltration-capacity are somewhat as shown by the line oob, Figure 4. Consider, for example, a loam soil having an infiltration-capacity as indicated by the horizontal line ac. The segment ra of this line is rainfall-excess rejected at the surface and which produces surface-runoff. The seg-

ment cs is rejected excess of infiltration over field moisture-deficiency and goes to the water-table. The remainder, represented by the intercept ac, represents the percentage of total rainfall which will be retained within the soil moisture-zone, presuming that vegetation is growing on the soil to the maximum extent which the soil can support. Similarly, the intercepts de and fg represent moisture available for vegetation in clay and sand. A series of intercepts similar to those described and corresponding to different infiltration-capacities has been taken off and plotted as shown by the line ohkm, Figure 4. This shows, as far as soil-moisture alone is concerned, the relative ability of soils of different infiltration-capacities to support vegetation from soil-moisture alone. The maximum point on this curve corresponds to a soil of medium texture. It is not possible at this time to convert this directly into a diagram expressing ability of a soil to support vegetation in terms of soil-texture. However, for illustrative purposes it may be assumed that infiltration-capacity and field moisture-capacity of the soil are linear functions of the texture or fineness. The result shown by the line oab, Figure 5, is then obtained (this corresponds to line ohkm, Fig. 4). This curve, derived solely from hydrological considerations, is in good agreement with practical experience. The curve shown is not symmetrical, and probably is not in fact. Heavy impervious soils because of their large field moisture-capacity can, with equal rainfall, tide vegetation over periods of drought better than coarse-textured soils. It is to be noted that this discussion does not take into consideration other requirements of vegetation than those for soil-moisture.

For a given rainfall-regime, that soil will best support vegetation which permits the largest percentage of the rainfall to be absorbed as infiltration and at the same time permits the smallest percentage of infiltration to pass downward to the water-table. For such a soil the surface-runoff will be relatively small, the water losses a maximum; the total runoff will not be large but will be somewhat regulated by ground-water flow; ground-water supplies will be of moderate amount but generally perennial.

Turning next to a consideration of the height of water-table, in a given phreatic basin with given rainfall characteristics this is controlled jointly by two factors, namely, (a) the amount of accretion to the water-table, and (b) the transmission-capacity of the soil. With the outlet level or sole of the aquifer fixed by topographic conditions, the average height of water-table at a given point within the phreatic basin will be such that, at the existing height, the average rate of outflow equals the average rate of accretion. If there is abstraction of water directly from the water-table by vegetation or evaporation, this is to be added to the outflow.

Considering first a case where there is no such abstraction, the rate of outflow is proportional to the product of depth of ground-water in the aquifer, the slope of the water-table and the transmission-capacity of the soil.

The amount of accretion to the water-table for a given soil and rainfall-regime is doubly a function of the infiltration-capacity, since, as f increases, fmc decreases and an increasing portion of the total infiltration passes downward to the water-table; hence the average rate and the total amount of accretion increase rapidly, other things equal, as the soil-texture becomes increasingly coarser. Transmission-capacity is also a rapidly increasing function of increasing size of soil-grains. Thus proceeding from finer to coarser-textured soils the total accretion to the water-table increases, thus tending to maintain a higher ground-water level. At the same time the transmission-capacity of the soil increases and this tends toward a lowering of the water-table. The combined action of these two opposing factors tends toward the maintenance of a more or less invariant mean ground-water level under widely differing soil-conditions. The effect of their joint operation is revealed by the fact that the surface water-table in well-drained humid regions is generally at a depth varying from 10 to 30 feet, in soils ranging from those of the finest to those of the coarsest textures. Ability of a given region to supply ground-water is, however, more or less proportional to the infiltration-capacity alone.

Starting with the finest-textured soils, as the coarseness of the soil increases, ability to support vegetation and to supply ground-water both increase, the ability to support vegetation reaches a maximum for a soil of medium texture and thereafter decreases, while ability to supply ground-water continues to increase.

Thus far it has been assumed that vegetation is supplied wholly from the zone of aeration or that there is no direct abstraction from the water-table by plants. If

the water-table is at a suitable but moderate depth, plants, including both native vegetation and cultivated crops, may and often do derive a part of their moisture-supply by direct abstraction from the water-table. For this condition the relation between soil-moisture and ability to support vegetation is considerably modified as compared with the case already considered, where the moisture-supply of vegetation is derived wholly from the zone of aeration. Assuming--as is apparently the case--that the plant derives moisture from the soil above the water-table and by abstraction directly from the water-table, respectively, in proportion to the facility with which it can get water from each, then the relation between soil-textures and ability of the soil to support vegetation will be somewhat as indicated by the dashed line oce, on Figure 5. The two curves on Figure 5 indicate, qualitatively, at least, the relative ability of a given soil to support vegetation according as there is or is not a water-table at a height within the reach of plant-roots. The purpose of this diagram is to show that the range of soil-textures through which mesophytic vegetation can thrive is, in general, considerably increased by the presence of a water-table of suitable depth.

Conclusions

Infiltration-capacity is an important physical characteristic of the soil. For a given soil the infiltration-capacity varies between a maximum value when the soil is dry and a minimum value after wetting and packing. The infiltration-capacity is generally close to the maximum during short storms following dry periods and close to the minimum during prolonged wet periods.

The infiltration-capacity of a drainage-basin can be determined from runoff and rain-intensity data and, conversely, if infiltration-capacity is known, in conjunction with rain-intensity data, the surface-runoff and total infiltration to the soil can be determined.

For small areas in and adjacent to cities, where rain-intensity records are available and estimates of storm-runoff are required in connection with sewer-design, the use of this method for estimating surface-runoff appears more rational than the so-called "rational method."

It is shown that rainfall-excess and infiltration-capacity are apparently two additional variables which need to be included in order to obtain a close correlation between runoff and the factors by which it is controlled.

Stream-rises are classified on the basis of infiltration-capacity and field moisture-capacity, and a definite procedure is established for separating ground-water flow from surface-runoff in streams.

There are close interrelations between infiltration-capacity, field moisture-capacity, growth of vegetation, and ground-water levels. It appears that natural vegetation generally develops to the maximum extent to which it can be continually supplied with moisture with a given rainfall-regime.

Owing to the fact that the demands of vegetation for moisture are incessant, whereas infiltration occurs intermittently and by quanta, that soil is best able to support vegetation which has a large infiltration-capacity and also a large field moisture-capacity.

Infiltration-capacity and field moisture-capacity are complementary, the first increasing and the second decreasing as the soil-texture ranges from fine to coarse. The best combination for plant-growth, from the viewpoint of hydrological considerations alone, is therefore a medium-textured soil within the class designated "loam."

There is a close correlation between total infiltration and the water-losses or water utilized directly or indirectly by vegetation, and total infiltration appears to be the best available basis of estimating the "effective rainfall" in relation to vegetation.

Voorheesville, New York

REVISED TEMPERATURE-FORMULAE FOR PREDICTING SEASONAL PRECIPITATION AND RUNOFF IN CALIFORNIA

A. F. Gorton

(Abstract)

Forecasts of seasonal precipitation in California based on observed ocean surface-temperatures at La Jolla during the midsummer upwelling-period correctly indicated an excess or deficit in practically three-fourths of the years from 1923 to 1931, but the divergence of computed and observed values in 1931-32 pointed to the need of a broader and more flexible index. Studies of the correlation between the precipitation or runoff and the ocean-temperatures of various months showed that a better fit might be secured by using values for certain months preceding as well as following the summer period.

The computations were performed by the ordinary least-squares method (Doolittle solution), also by a related method in which the element predicted is expressed as a joint function of two temperature factors

$$R = (a + bx)\ (c + dy) = A + Bx + Cy + Dz$$

where x, y are the temperature-factors, z is their product, and the coefficients A... are fitted by least squares. (In this case, actually y = current winter temperature, x = difference between preceding summer and preceding winter-temperatures.)

These new formulae resulted in a much better verification than previous ones, when applied to the chief rainfall- and runoff-areas in northern California. For Huntington Lake District rainfall and Owens River runoff, agreement of sign of the departures was noted in 13 years out of 16, and the probable error was as low as 10 and 13 per cent, respectively, for the interval 1916-30. When air-temperatures at San Diego were substituted for ocean-temperatures at La Jolla, as an index, the error increased by several per cent, probably on account of the inherently variable nature of the former. [The complete paper will appear in Proceedings of the Fifth Pacific Science Congress.]

Scripps Institution of Oceanography,
La Jolla, California

A STUDY IN EVAPORATION AS AFFECTING THE RUNOFF OF OWENS RIVER, CALIFORNIA

Clem A. Copeland

The Bureau of Power and Light of the City of Los Angeles has been carrying on extended research for several years with the object of predicting the runoff of the Owens River and its tributaries which furnish the City with water and electric energy. Short-time predictions involving the expected runoff for the next year as indicated by phenomena of the previous year, have been made by means of least-square correlations of the ocean-temperatures at La Jolla, the air-temperatures of Tokyo, the precipitation at Nevada City, and other similar factors.

Based on the temperatures of the ocean six feet below the surface at the end of Scripps Pier at La Jolla, the prediction for the runoff of Owens River for 1932 was extravagantly high, there having been in 1931 the most unusually high temperatures since 1916 when records were initiated at this point. Other indications together with the La Jolla temperatures resulted in a final prediction of 125 per cent of the normal of 225 second-feet runoff of the River for 1932. The winter of 1931-32 seemed auspicious for fulfilling this prediction as the snowfall was the heaviest of any winter for the last 16 years. The actual runoff fell far short of the prediction, being 188 average second-feet, or 83.6 per cent of normal. The present concern is in determining the reason for the discrepancy.

By July, 1932, the deficiency was becoming apparent. It so happened that the author, in charge of the Research and Records Section of the Bureau of Power and Light

Fig. 1--Topographic map of region about Convict Creek and Convict Lake (after U.S. Geological Survey--readjustment indicates elevations given should be decreased 7 feet)

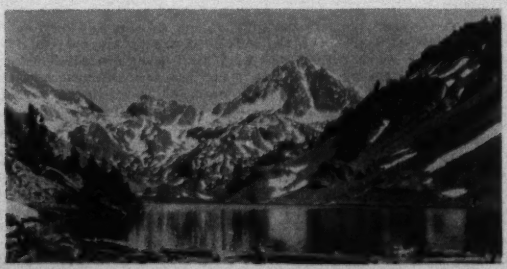


Fig. 2--Upper reaches of Convict Creek with the backbone of Sierra Nevadas in background and Lake Mildred, whence Convict Creek issues in foreground; the high peak on the backbone is Red Slate Mountain, 13,152 feet in elevation

Table 1--Climatological data at entrance to Owens River Gorge on Owens River, July 1932

Date	Weather	Temperature Max.	Temperature Min.	Wind-direction	Runoff of Convict Creek at C	Approximate relative flow No-Name Creek at Camp A	Temperature Convict Lake Camp A Just before sun-up	Temperature Convict Lake Camp A Middle of day
1932		°F	°F			c/o	°F	°F
July 1	Cloudy	96	40	South	190.0	...	..	..
2	Clear	82	42	Calm	187.0	...	..	..
3	.....	..	..	.....	187.0	...	..	..
4	.....	..	..	.....	180.3	...	..	..
5	Clear	98	43	West	157.6	...	..	..
6	Clear	98	40	West	137.0	...	..	..
7	Clear	100	43	West	129.4	...	..	..
8	Clear	92	44	West	124.6	...	..	..
9	Clear	92	40	West	133.0	...	..	..
10	.....	..	..	.....	131.1	...	..	48[a]
11	Clear	88	36	Calm	124.9	100	42[a]	50[a]
12	Clear	84	32	West	116.1	100	42[a]	50[a]
13	Pt.cl'dy	74	36	North	108.0	125	44	61
14	Clear	81	30	North	94.0	100	50	60[a]
15	Clear	86	32	North	83.5	90	46	60[a]
16	Clear	90	34	West	80.1	90	44	58[a]
17	.....	..	..	.....	80.1	75	45[a]	60[a]
18	Clear	96	40	West	81.8	50	46[a]	65[a]
19	Clear	80	28	West	81.8	35	48	70
20	Clear	84	30	North	76.7	30	44	70[a]
21	Clear	88	34	West	72.2	25	44	70
22	Clear	95	40	West	70.8	0	60	72[a]
23	Clear	94	38	North	72.2	0	52	73[a]
24	.....	..	..	.....	75.0	...	..	..
25	Clear	95	35	Calm	75.0	...	..	..
26	Clear	94	38	North	73.6	...	..	..
27	Clear	95	38	West	70.8	...	..	..
28	Clear	92	40	West	66.6	...	..	..
29	Clear	96	40	West	65.2	...	..	..
30	Clear	90	38	North	63.4	...	..	..
31	Clear	..	..	.....	61.0	...	..	..

[a] These observations are not actual statistics; they are inserted from memory to illustrate more fully the very uniform trend of increasing temperatures night and day which actually occurred during the period over ideally clear beautiful weather. Convict Lake Camp A was reached at 11 a.m. July 10 and was left at 2:30 p.m. July 24.

of the Department, camped from July 10 to 23, 1932, on the shore of Convict Lake on the northeastern slope of the Sierra Nevadas and 41 miles by highway from Bishop, California. He made observations which, while incomplete--due to absence from the camp on various expeditions during the daytime--were of importance in determining the cause of the deficiency of runoff.

Convict Creek which flows into and out of Convict Lake is probably representative to a sufficient extent of conditions of the inflow to Owens River of which Convict Creek is an important tributary, except that the Creek is, perhaps, a more turbulent stream than the average of several. The Creek sources principally at the head of a valley or basin whose highest reaches are on the ridge of the Sierra Nevada Mountains, the ridge averaging about 12,500 feet in elevation. The relatively small floor of the Creek's runoff-basin contains Lake Mildred, perhaps 0.8 square mile in area, and a level meadow of about a square mile in extent. The meadow land is of decomposed granite and decomposed and broken metamorphosed rocks. The entire basin apparently is of solid metamorphosed rock which undoubtedly underlies the meadow and Lake Mildred.

Other auxiliary or tributary basins of the same geological construction, feed Convict Creek, as shown by the topographic map (Fig. 1), one being that containing Lake Dorothy and another containing Lake Genevieve, as well as that containing "No-Name" Creek. From these sources Convict Creek flows turbulently over solid meta-

morphosed rock, almost due north, from an elevation of 10,000 feet at the outlet of Lake Mildred to Convict Lake of elevation 7,583 feet, a distance of about four miles. The Creek then emerges from the Lake and flows over a glacial moraine to the valley-plain, which is drained by Owens River.

The outlet of this valley is at the mouth of Owens River Gorge, as shown at "G" on the quadrangle, where some of the observations on Table 1 were made. "G" on the map shows where, on Convict Creek, the water-measurements are made, as a routine affair, by the Bureau of Water Works and Supply of the Department.

Table 2 shows the evaporation during July at "G" over a period of years, taken by the same observers. The early morning and midday temperatures were taken at the camp shown at "A" on the map in the center of a sparse cottonwood forest, at the edge of Convict Lake and within 100 feet of the mouth of a small unnamed stream which we will call "No-Name Creek." The midday temperatures were taken in the shade. The early morning temperatures were undoubtedly the coldest of the night. With the interruption of one day upon which a slight snow-storm occurred during the early morning hours of July 13, the weather was beautiful and clear all day each day and night except for a slight cloudiness during two days. The snow had been dissipated by noon July 13.

Table 2--Evaporation at entrance to Owens River Gorge, month of July, 1920-32
(From pan-measurements for entire month at "G")

Month	Evaporation	Month	Evaporation	Month	Evaporation
	inches		inches		inches
July 1920	6.37	July 1925	4.49	July 1930	5.37
July 1921	7.01	July 1926	5.01	July 1931	6.20
July 1922	6.15	July 1927	3.30	July 1932	6.23
July 1923	7.66	July 1928	5.28		
July 1924	5.75	July 1929	3.76	Average	5.58

Upon return to the office in Los Angeles on July 25, the anomaly of a uniformly increasing temperature with a uniformly decreasing runoff of Convict Creek was freely discussed and at first explained as an absorption-phenomenon or sinking away of water due to having had an exceedingly dry previous year which left the ground--especially the porous terminal moraine--dry, parched, and "thirsty" for the melting of the snows.

The action of "No-Name Creek" whose outlet is at "A" on the map from which water for the camp was supplied is important in this connection and seemed to point definitely to the true reason. This Creek was a turbulent small stream flowing over a rocky bed, the latter part for a half mile of its length, being very steep, down the side of a lateral glacial moraine some 300 feet in height. An attempt has been made to show the action of this Creek which flowed perhaps two second-feet on July 11. On July 16 no water reached the camp between 10:00 a.m. and 4:00 p.m. On July 17 none reached the camp between 10:00 a.m. and 5:00 p.m. On July 19 none reached the camp from 9:00 a.m. until 6:30 p.m., and on July 23 no water reached the camp even early in the morning.

Now as to snow-conditions, as far as could be observed without actual measurements there appeared to be fully as much snow at the end of the period as at the beginning. Immense thick snow-fields covering perhaps 30 per cent of the area of the water-sheds existed at the sources of Convict and No-Name creeks not apparently diminishing in area during the period from July 11 to 23, inclusive.

Figure 2 shows the snow-conditions during the vacation-period in the Lake Mildred basin source of Convict Creek. The roof of the Sierra Nevadas is seen in the background.

The mile-and-a-half long "snow-wedge" in the bottom of Convict Creek Canyon below Lake Mildred began to cave in on July 21 above Convict Creek which had been flowing through a tunnel underneath. These rough observations are recorded thus, in the hope that others may recall similar phenomena. It would seem that only evaporation of almost incredible proportions would account for the observed phenomena and for the

very great deficiency in the runoff of Owens River in 1932 which should have resulted from the excessive snowfall of the 1931-32 winter-season.

Research and Records Section, Bureau of Power and Light,
City of Los Angeles, California

LIMITATIONS OF THE DALTON FACTOR IN EVAPORATION

Robert E. Kennedy

The time-honored but erroneously labeled Dalton factor has been accepted by all workers in the study of evaporation and incorporated in their computations in one way or another. It is included in the denominator of the Bowen ratio R in the researches of the Scripps Institution of Oceanography. Stated briefly, it is to the effect that if all other factors are constant the rate of evaporation is proportional to the vapor-pressure deficit, meaning the difference between the saturated vapor-pressure at the water-temperature and the actual vapor-pressure of the atmosphere. A great body of experimentation has proved its validity within a certain range of conditions.

There are two situations, however, in which it fails. First, when the water is warmer than the air and the air is fully saturated there will be a computed difference which indicates evaporation. But if the air is saturated there can be no evaporation.

This is illustrated in Rohwer's experiments with a heated water-surface. In commenting on them he says (Carl Rohwer, Tech. Bull. No. 271, U.S. Dept. Agri., p. 28), "The table shows that except for periods of heavy snowfall there is a fairly close agreement between the observed and computed ....." He thought the difficulty was due to the wind blowing some of the snow out of the rain-gage. That may account for part of the discrepancy but a larger part must be charged to the failure of the theory to meet that particular condition.

These experiments were conducted by Rohwer to check the interesting suggestion offered by Freeman (John R. Freeman, Regulation of Great Lakes and effect of diversions by Chicago Sanitary District, Chicago Sanitary District, Chicago, Ill., p. 146) that evaporation from the Great Lakes may be actually greater in the winter than in summer because the water is kept from freezing by wave-action. So its surface-temperature is 32° F.

The experiment tends to prove Freeman's idea correct. The theory is quite applicable except for the small per cent of the time the lakes are covered with fog or storm.

It fails again apparently or at least it reveals an unexpected condition when the reverse condition prevails and the water is cooler than the air. Freeman (reference as above, pp. 110, 116) reports that this occurs much of the time over the Great Lakes in the summer. The average air-temperature over Lake Michigan, for instance, is 63°3 F and the water-temperature is 56° F during June. Then a negative difference in vapor-pressure occurs for all relative humidities above 77 per cent. A negative evaporation would be precipitation which can occur only when the relative humidity is about 100 per cent. When the water is colder than the air it may actually collect some vapor out of the immediately adjacent atmosphere. The actual contribution would probably be negligible, but there certainly would be no evaporation for there would be no chance for the liberated molecules to get away. It would be a sub-adiabatic condition in meteorological parlance.

When the reverse condition prevails, the water is warm and the air is cold, the temperature-gradient is reversed. Masses of moist air warmer than the surrounding atmosphere rise as long as their loss of temperature per unit of altitude is less than that of the surrounding air. Thus molecular escape is encouraged.

Part of the difficulties found in developing a formula based primarily on the Dalton factor may be due to the inability to properly appraise the relative humidity for the unit of time used. Moreover, water-temperatures are usually not available. Then the less reliable factor, the saturation-deficit of the air must be used. Theis (C. V. Theis, Some recent studies in evaporation, Trans. Twelfth Annual Meeting Amer. Geophys. Union, p. 222) proposed a combination of the three daily readings by averaging

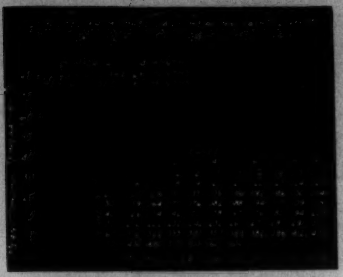
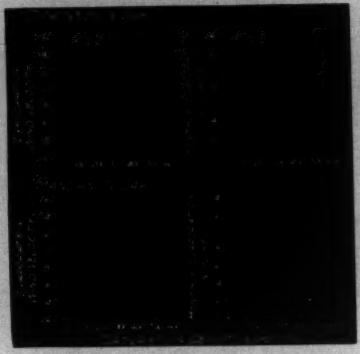


Fig. 1--Monthly saturation-deficit in inches mercury, computed from three daily readings (AM + 2N + PM)/4



Figs. 2 and 3--Monthly evaporation in inches at United States Bureau of Plant Industry stations Dickinson and Mandan, North Dakota

the morning and noon with the noon and evening reading thus: (AM + 2N + PM)/4. Night evaporation is ignored. The curve of monthly saturation-deficits shown on Figure 1 was obtained by thus computing the deficit for each of the three daily readings for each day of the month and plotting the monthly average against the mean air-temperature for the month.

These saturation-deficits appear to give fairly consistent results with the monthly data obtained at the two Great Plains field-stations of the United States Bureau of Plant Industry now active in North Dakota--one at Dickinson and one at Mandan.

In Figure 2 the monthly evaporation is divided by the average monthly wind-velocity and the result plotted with the saturation-deficit. In Figure 3 the wind-velocity is ignored and omitted with results fully as consistent. A working formula could be taken from either Figure. Preference is had, of course, for the omission of the wind-velocities for at the ground-levels they are largely affected by local conditions and are usually small in any event.

This further indicates that the search for an adequate and universally applicable evaporation-formula probably lies in the direction blazed out by the Scripps Institution of Oceanography. Meanwhile we must apply the few tentative reservoir-factors available to the voluminous pan-data scattered throughout the country.

State Engineer Department,
Bismarck, North Dakota

A TEN-YEAR RECORD OF WATER-TABLE FLUCTUATIONS NEAR RUNYON, NEW JERSEY

Henry C. Barksdale

The fluctuations of the water-table in the vicinity of Runyon in Middlesex County, New Jersey, have been observed from August, 1923, to the present time by the United States Geological Survey, the New Jersey Department of Conservation and Development, and the New Jersey State Water Policy Commission. During most of this time the author of this paper has been actively associated with this work. A water-stage recorder has been maintained on one well, the so-called Morrell well, throughout the whole period. Water-stage recorders have also been installed on other water-table wells in the region for shorter periods and periodic measurements of water-level have been made on about 35 wells. Some of the results of these observations and brief comments upon them are presented herein.

The location of the region in which the wells discussed in this paper are situated is shown in Figure 1. It lies in the northwestern part of the New Jersey Coastal Plain and the wells penetrate the usual unconsolidated Coastal Plain sands and clays.

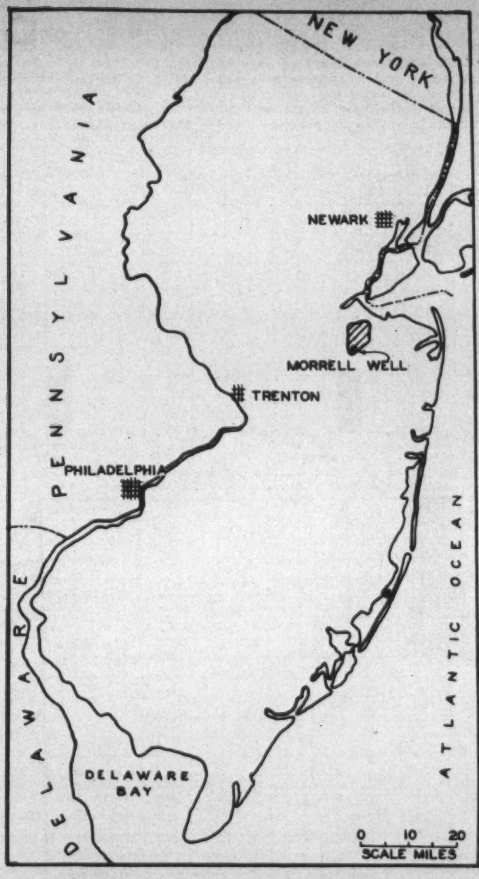


Fig. 1--Map of New Jersey showing location Morrell Well and boundary-line of region including the other wells observed

The scale of the map is too small to show the location of each of the 35 wells on which periodic tape-measurements of water-levels were made, but the location of the Morrell Well is shown and a boundary-line drawn to include all the other wells. The topography of the region is rolling and the altitude of the ground-surface at the observation-wells varies from about 20 feet to about 130 feet above mean sea-level. The altitude of the ground-surface at the Morrell Well is approximately 75 feet above sea-level.

The Morrell Well is a dug well about eight feet deep. It was dug for use with a water-stage recorder and has been used for that purpose exclusively. It is situated

in a flat almost swampy valley where the water-table is normally near the surface and vegetation is quite heavy. The valley is drained by three small streams which are dry in all but the wettest summers. The principal material encountered in digging the well was a fine, clayey, black sand. A rain-gage is installed near the Morrell Well to facilitate the study of the effects of precipitation on the water-table.

There is a great difference in the way in which a given amount of precipitation affects the water-table at the Morrell Well under different conditions. When the

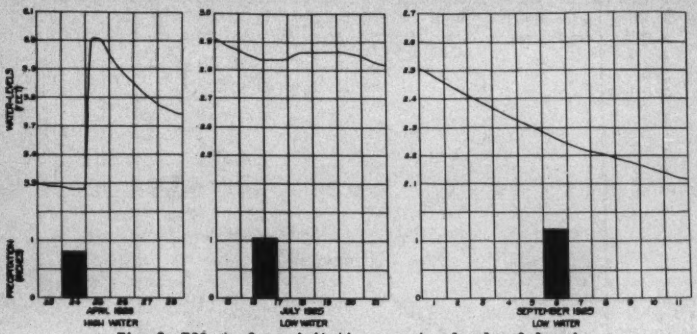


Fig. 2--Effect of precipitation on water-levels of Joseph Morrell Well, April, July, and September, 1925

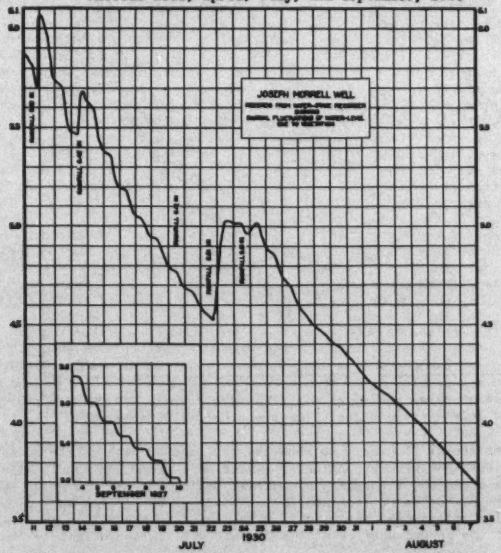


Fig. 3--Diurnal fluctuations of water-level, Joseph Morrell Well, July to August, 1930

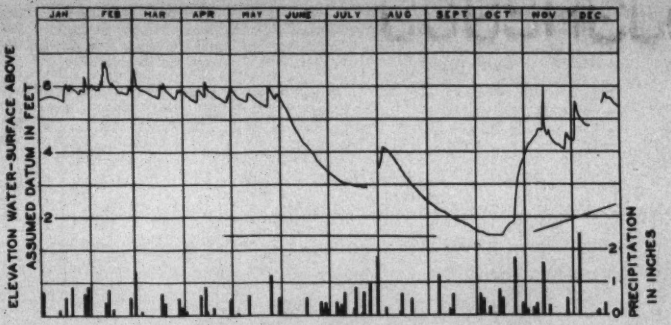


Fig. 4--Graph showing water-levels in the Morrell Well and daily precipitation for year 1925

water-table is high, especially in winter when the plants are dormant, a moderate rain-storm produces a sharp rise in the water-table. At such times the capillary fringe probably extends up to the surface and the additional water from precipitation takes immediate effect in raising the water-table, there being little opportunity for storage in the soil above the water-table. If plants are growing at such times, they are already plentifully supplied with moisture and cannot take up any of the additional moisture from precipitation. On the other hand, when the water-table is low and the plants are growing, a considerable amount of rain may fall without producing any noticeable effect upon the water-table. The upper part of the soil is then dry and affords storage for a considerable amount of water and the plants are in condition to absorb additional moisture readily and return it to the air by transpiration, so that very little, if any, water reaches the water-table. Figure 2 illustrates these different conditions. On April 24, 1926, a rainfall of 0.80 inch produced an immediate rise in the water-table of 0.53 foot after which the water-level fell off gradually as the soil was drained into the nearby streams. On July 16-17, 1925, a total precipitation of 1.05 inches produced only a very slight rise, and on September 6, 1925, a rainfall of 1.21 inches did no more than reduce temporarily the rate of lowering of the water-table.

The effect of vegetation upon the water-table is still more strikingly shown by the daily fluctuations of the water-table shown in Figure 3. During the growing season, these fluctuations occur almost invariably in warm clear weather, when the water-table is falling and is between one foot and three feet below the surface of the ground. They seem to be caused by the varying demands of plants for water during the day, when the air is warm and dry, and during the night, when it is comparatively cool and moist. At the Morrell Well, these fluctuations usually appear on falling stages only, since the rising stages are always associated with precipitation, so that the plants do not need to draw upon the water-table for moisture. Furthermore, the rising stages are usually rapid enough to cover up any such effect if it should occur. The occurrence of these fluctuations is also limited by the depth from which the roots of the plants in the vicinity can draw water freely from the water-table. When the water-table is more than three feet below the surface, either the plants take no water from the water-table, or they are unable to draw it up at a rate which more than satisfies their night-time demands, and the fluctuations disappear, as at the lower end of the line in Figure 3. The inset in the Figure shows a period when the lowering of the water-table seems to be due almost entirely to the demands of vegetation, since the water-level remains almost constant at night when the plants are drawing very little water from the soil.

A daily fluctuation similar to that just referred to, has been observed on one or two occasions in the winter, when the plants were dormant. On one occasion they ap-

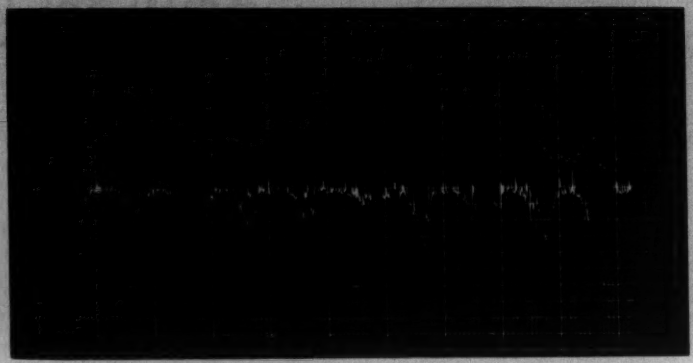


Fig. 5--Graph showing average fluctuation of water-level in 35 observation-wells, fluctuations of the water-level in the Morrell Well, and monthly precipitation from 1923 to 1933

peared when the water-table was very near the surface and the weather fair and windy. These fluctuations are attributed to direct evaporation from the soil. On another occasion, a somewhat similar fluctuation was observed when the ground was covered with snow, which melted during the day and not during the night.

Figure 4 shows the fluctuations of the water-level in the Morrell Well and the daily precipitation for the year 1926. During the winter, when the water-table is high and the plants dormant, each moderate rain-storm produces an immediate rise in the water-level, which then gradually recedes until the next storm, giving the line representing the water-level, a ragged, saw-tooth appearance. In summer, when the water-table is low and vegetation is in full growth, the water-table is much less affected by precipitation, and the line representing the water-level becomes more of a smooth curve. It is interesting to note the large amount of precipitation which fell in the month of July without affecting the water-table materially, until the heavy storms at the end of the month. Another point of interest is the snow-fall of January 2, followed by a gradual rise in the water-table as the snow melted. During the wet summer of 1926, the water-table was high all of the time and the hydrograph retained its saw-tooth appearance throughout the year.

The 35 wells in which tape-measurements of water-level are made, vary in depth from 10 feet to 48 feet. Four of them are shallow 7-inch test-wells driven for observation-purposes only, and 31 are dug wells used for domestic water-supplies at farm homes. A study of the behavior of the water-levels in these wells indicated that it was advisable to separate them into two groups on a basis of depth. The first group is composed of 30 wells all under 25 feet in depth and practically all under 20 feet in depth. The second group is composed of five wells over 25 feet in depth and ranging up to 48 feet in depth. Figure 5 shows the average fluctuation of the water-level in these two groups of wells together with the fluctuations in the Morrell Well and the monthly precipitation at the Morrell Well for the entire period covered by our observations. During 1923, and part of 1924, the lines representing the average fluctuations in the wells measured periodically, are based upon observations on too few wells to be very significant as averages, but they are given for what they are worth. From July, 1929, to August, 1931, only the four 7-inch observation-wells were measured. During this period, the line representing the fluctuations of the shallow wells is based on observations on these wells only, and the line representing the five deep wells is necessarily discontinued.

In general, the line representing the water-level in the Morrell Well exhibits the characteristics shown for 1925 in Figure 5. During the autumn of 1932, this well

went dry for the first time since it had been in service. Near the end of September it was deepened from its original depth of about 6 feet to a depth of 8-1/2 feet. The water-levels observed in it in the early part of October, 1932, are the lowest on record for this well.

The shallow wells respond quickly to changes in precipitation and in the demands of vegetation for water. It is interesting to note the general similarity of the line representing the average fluctuation of water-level in these wells, to that representing the fluctuations in the Morrell Well. When it is considered that this line is based upon groups of measurements made at times chosen at random, without reference to the probable position of the water- table in the region, this similarity is even more striking.

The deep wells do not respond quickly to changes in precipitation or in the demands of vegetation, due to the greater time required for water to travel through the soil and reach the water-table. When the line representing the average water-level in these wells is compared with those for the shallow wells and for the Morrell Well, an appreciable lag is observed. Instead of reaching their low point in the summer, when the precipitation is usually low and the demand of vegetation is greatest, these wells continue to drop until some time about the first of the following year, when they normally reach their lowest level and begin to rise. A study is being made of this lag with the object of determining, if possible, the rate at which ground-water moves through the soil. Apparently several months are required, under the conditions which exist in the Runyon Region, for the water derived from precipitation to move from the depth of the shallow wells down to that of the deep wells. The deep wells also seem to carry over from one year to the next some of the effects of drought or of wet weather. The downward trend from August, 1924, to January, 1926, and the longer upward trend from January, 1926, to August, 1928, are examples of this behavior.

For several years the water-levels in the Morrell Well have been furnished weekly to the New Jersey State Forest Fire Service, who are making a study of the conditions affecting the occurrence of forest-fires and the possibility of predicting them. It is believed that when the water-table is high, so that the capillary fringe extends to the surface of the ground, the leaves and trash on the forest-floor will be moist and less likely to burn than in times of low water-table and dry soil-conditions. The water-levels in this well are, of course, only one of a large number of factors considered by the New Jersey Forest Fire Service in this connection, but it is an interesting and perhaps unique use for records of ground-water levels.

During 1932, gaging-stations were established on three small streams in the Runyon Region and continuous records of the flow in these streams will be available for study in connection with the records from the Morrell Well and from the other water-table wells which are being measured periodically in the region. It is believed that some interesting results may be obtained correlating the fluctuations of the water-table with those of the flow in nearby small streams.

The record of water-table fluctuations in the Runyon Region is believed to be among the longest of such records in the eastern part of the United States. This work was originally undertaken as a means of studying the problems of ground-water storage and the withdrawal of water from the soil by plants. It has proven well worth while in this connection and has increased in value as new uses for the records have appeared.

U. S. Geological Survey and New Jersey State Water Policy Commission,
Trenton, New Jersey

FLUCTUATIONS OF WATER-SURFACE IN OBSERVATION-WELLS AND AT STREAM GAGING-STATIONS IN THE MOKELUMNE AREA, CALIFORNIA, DURING THE EARTHQUAKE OF DECEMBER 20, 1932

Arthur M. Piper

On December 20, 1932, much of the western United States felt a pronounced earthquake-shock which caused noticeable fluctuations of the water-surface in several observation-wells and at two stream gaging-stations in the Mokelumne Area, central

Table 1--Wells in Mokelumne Area equipped with water-stage recorders during earthquake of December 20, 1932

Well No.	Location	Diameter of well	Depth of well	Amount of casing	Altitude ground-surface above sea-level	Mean altitude above sea-level water-surface in well, Dec. 20-21, 1932	Mean depth of water above bottom in well Dec. 20-21, 1932	Amplitude of water-surface fluctuation during earthquake: Rise (+)	Amplitude of water-surface fluctuation during earthquake: Fall (-)
		inches	feet	feet	feet	feet	feet	feet	feet
	T. 3 N., R. 6 E.								
5612A2	NW ¼ NW ¼ sec. 12	6	76.0	..	46.9	23.78	52.9	0.490	0.266
5626R5	SE ¼ SE ¼ sec. 25	10	107.0	..	41.4	16.15	61.8	0.20[b]	0.03[b]
5626R4	SE ¼ SE ¼ sec. 25	12	40.0	40[c]	41.2	16.16	16.0	None	None
	T. 3 N., R. 7 E.								
5710K3	NE ¼ SW ¼ sec. 10	10	57.0	57[d]	72.4	33.88	18.5	None	None
5710K4	NE ¼ SW ¼ sec. 10	12	190.0	160	72.2	33.92	151.7	0.065	0.186
	T. 4 N., R. 7 E.								
4722Q4	SW ¼ SE ¼ sec. 22	10	51.0	49[d]	53.6	43.10	10.5	None	None
4722Q5	SW ¼ SE ¼ sec. 22	9	266.0	149	83.8	44.02	226.2	0.240	0.206
4734K3	NE ¼ SW ¼ sec. 34	10	51.8	48	82.2	47.62	17.1	None	None

[a]Fluctuation caused by earthquake disregarded
[b]Approximate
[c]Lower 20 feet perforated
[d]Lower 10 feet perforated

California. These effects of the earthquake are reported briefly in this paper.

According to Dr. Byerly (personal communication, February 9, 1933), in charge of the seismograph-station of the University of California at Berkeley, the earthquake-vibrations at that place began at $10^h\ 11^m\ 00^s$ p.m., Pacific Standard Time, December 20, 1932, and continued three hours on the records of his most sensitive instruments. He reports further that the maximum double amplitude of the Earth-motion at Berkeley was of the order of two mm and that the north-south and east-west components of the amplitude were approximately equal. In the Mokelumne Area, which con-

ters about the City of Lodi, 57 miles north 70° east from the seismograph-station at Berkeley, the pronounced initial Earth-shock caused chandeliers to sway, upset some bric-a-brac, and in at least one building opened a few cracks in the interior plastering. At Stockton, 15 miles south of Lodi, the glass of at least one display-window in a shop was cracked.

The Mokelumne Area is situated on the main valley-plain of the California Trough and in the central eastern part of that physiographic feature. The land surface is underlain by unconsolidated alluvial deposits of Pleistocene and Pliocene age down to a depth of about 150 to 500 feet; these deposits are underlain in turn by semi-consolidated sediments of Tertiary age down to a depth of at least 1,975 feet. A test-well for petroleum which was drilled to a depth of 4,751 feet near Oakdale, 34 miles southeast of Lodi, did not pass through the Tertiary sediments. The crystalline rocks that form the core of the Sierra Nevada crop out in the foothills 23 miles east of Lodi and were encountered at a depth of 1,214 feet in another test-well 22 miles northeast of Lodi. These and other features of the geology of the Mokelumne Area are described in a recent report by Hoyt S. Gale (H. S. Gale, A. M. Piper, and H. E. Thomas, Geology of the Mokelumne River Basin, California, U. S. Geol. Sur. manuscript report, released to the public Dec. 23, 1932, Lodi, California).

At the time of the earthquake water-stage recorders were being operated by the United States Geological Survey on eight observation-wells in the Mokelumne Area. Descriptions of these wells and the magnitude of the fluctuation of the water-surface during the earthquake are given in Table 1.

Four of these eight observation-wells—Nos. 3625 R4, 3710 K3, 4722 Q4, and 4734 K3—extend only 10 to 20 feet below the water-surface; in them the water-surface indicates the level of the water-table in the surrounding alluvium. The charts from the water-stage recorders on these four wells indicate that the water-surface did not fluctuate during the earthquake. The remaining four wells--Nos. 3612 A2, 3625 R3, 3710 K4, and 4722 Q5--extend 50 to 200 feet below the water-surface. These are tightly cased nearly to the bottom and in them the water-surface indicates the hydrostatic pressure in relatively deep permeable beds that contain confined water. During the earthquake the water-surface in each of the deep wells rose above and fell below its normal level. Hence it appears that the water-surface fluctuated only in those wells which tapped bodies of confined ground-water. This conclusion is supported by the fact that six of the wells are arranged in pairs of one shallow and one deep well only a few feet apart; thus is eliminated the possibility that the water-surfaces fluctuated differently owing merely to local differences in the mode of occurrence of ground-water. The three pairs are wells 3625 R3 and R4, 3710 K3 and K4, and 4722 Q4 and Q5. Further, all the water-stage recorders are of the same type, the well-known Stevens type-E recorder. Also, at the time of the earthquake these recorders were installed so that the planes of their float-wheels lay in different quadrants of the compass, although the float-wheels of the two recorders at each pair of wells were parallel to one another. Thus differences in the mechanical features of the recorders and in the orientation of the recorders with respect to the direction of maximum amplitude of the Earth-vibrations fail to explain adequately the observed difference in the behavior of the shallow and deep wells.

The water-stage recorder charts from well 3612 A2 and from two of the three pairs of wells are reproduced in an accompanying diagram (Fig. 1) to indicate the fluctuations of the water-surface on December 20 and 21, 1932. In this diagram the trace of the water-surface for the deep wells is indicated by a heavy line, the trace for the shallow wells by a light line. The effect of the earthquake on the water-surface is indicated by the single vertical line that crosses the normal trace just to the left of the time-coordinate that separates December 20 and 21. Seemingly the fluctuations are the result of a single momentary pressure-wave. Whether the water-surface first rose and then subsided is not indicated clearly by the charts, for the traces of the two directions of fluctuation are superposed. However, the greater magnitude of the upward fluctuation on all the charts does suggest that the water-surface first rose and then subsided a less amount as the effect of the Earth-shock died out. On the original charts from wells 3612 A2 and 4722 Q5 the vertical trace produced during the earthquake is somewhat wider where it crosses the normal trace, as though the oscillation of the water-surface continued for several minutes with diminishing amplitude, but even this is not conclusively indicated. If the oscillations did continue in this

Fig. 1--Water-stage recorder graphs from observation-wells in Mokelumne Area, California, showing fluctuations of water-surface during earthquake of December 20, 1932

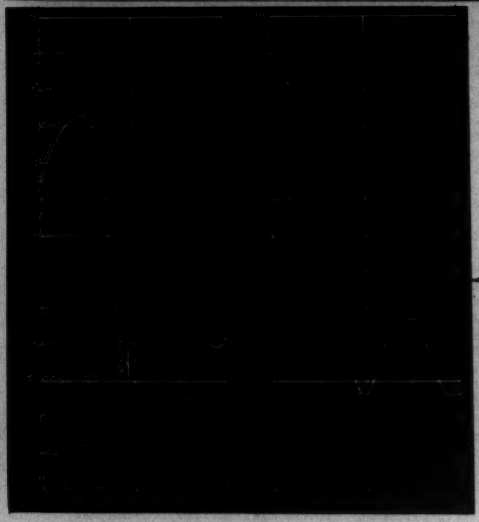


Fig. 2--Water-stage recorder charts from gaging-stations in Mokelumne Area, California, showing fluctuations of water-surface during earthquake of December 20, 1932

way they would not have been plainly traced on a water-stage recorder chart unless the time-scale had been inordinately extended.

On the chart from well 3710 K4 the trace of the water-surface after the earthquake is displaced downward an amount equivalent to 0.165 foot with respect to the trace before the earthquake. However, when the recorder was inspected on December 27, the measured altitude of the water-surface agreed with that indicated by the trace. Evidently the downward displacement was not due to mechanical derangement of the instrument but reflected an actual subsidence of the water-surface. This subsidence suggests that the earthquake produced locally in the water-bearing bed a condition of elastic strain which was dissipated so gradually in the ensuing six days that it did not cause any abnormal deflection of the trace. On the charts from wells 3612 A2 and 4722 Q5 the trace is displaced upward 0.035 foot and 0.010 foot, respectively, but these small amounts may well be due merely to sluggishness of the recorder.

During the earthquake eight water-stage recorders were also in operation at gaging-stations in the Mokelumne Area, six of the stations being on the Mokelumne River and two on the diversion canal of the Woodbridge Irrigation District. Of the six stations on the river, the charts from only two showed any effect of the earthquake. These effects were merely pronounced dots on the traces of the water-surface, as though the recording-pencil momentarily was thrown forcibly against the chart. Thus the effects seem only mechanical. However, the charts from the stations on the Woodbridge Reservoir (canal forebay) and on the Woodbridge Canal just below the headgate both indicate that the water-surface fluctuated noticeably during the earthquake. Another diagram (Fig. 2) reproduces the charts from the water-stage recorders at these two stations on December 20 and 21, and indicates the respective double amplitudes of the fluctuation to have been 0.08 and 0.04 foot. Both these stations are on small landlocked bodies of water which at the time were flowing only sluggishly. Under these conditions the earthquake may well have induced on the water-surface momentary ripples of the magnitude indicated by the charts. That similar ripples were not produced at the stations on the River may be fortuitous.

U. S. Geological Survey,
Lodi, California

SPECIFIC YIELD DETERMINED FROM A THIEM'S PUMPING-TEST

L. K. Wenzel

The specific yield of a water-bearing formation is defined as the ratio of (1) the volume of water, which after being saturated, it will yield by gravity to (2) its own volume (O. E. Meinzer, Outline of ground-water hydrology, U. S. Geol. Sur. Water-Supply Paper 494, p. 28, 1923). It is a measure of the quantity of water that a formation will yield when it is drained by lowering of the water-table. The determination of the specific yield is essential in many quantitative ground-water investigations.

In 1931 a pumping-test was made in the Platte River Valley, in Nebraska, to determine by Thiem's method the permeability of the water-bearing sand and gravel that underlie the Valley. This test, which constitutes a part of a cooperative investigation by the Conservation and Survey Department of the University of Nebraska and the United States Geological Survey, was briefly described in the 1932 Transactions of the American Geophysical Union (p. 393). The well was pumped continuously for 48 hours, and measurements of the discharge were made every 30 minutes. During the period of pumping and after pumping stopped about 5,000 measurements were made of the depths to the water-surfaces in 80 observation-wells, which were located on lines radiating from the pumped well to distances up to 1,200 feet. Instrumental levels were run to the measuring points on each of the wells so that the altitudes of the water-surfaces could be determined for any time. From the data obtained in this test the average coefficient of permeability was computed to be about 700. In the present paper a method is presented for determining the specific yield of the water-bearing material from the data collected in this test, and the results of the computations are given. This method for determining specific yield was suggested by Meinzer (O. E. Meinzer, Outline of methods for estimating ground-water supplies, U. S. Geol. Sur. Water-Supply Paper 638-c, p. 136, 1932).

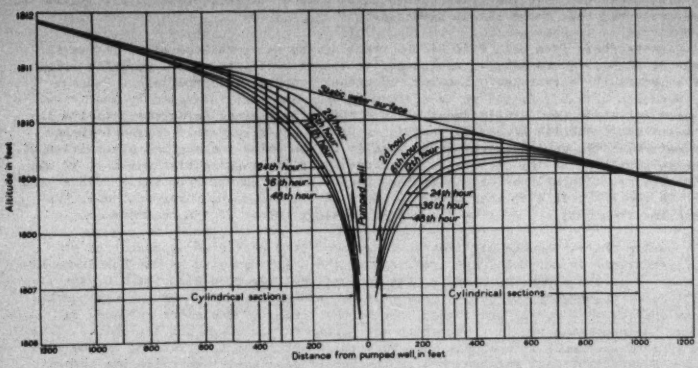


Fig. 1--Profiles of the cone of depression at several times after pumping began and location of cylindrical sections used for computing specific yield

Using the measurements of depths to water in the observation-wells, drawdown curves were plotted for each well, and profiles were constructed of the cone of depression after 2, 8, 12, 24, 36, and 48 hours of pumping. Only profiles obtained along a section parallel to the direction of natural ground-water movement are given in this paper (Fig. 1), because it was found that the values for specific yield computed from these profiles were approximately equal to the values computed from profiles along sections at other angles with the natural hydraulic gradient. The total volume of sediments unwatered in each of the successive periods and the volume unwatered in each ring as shown in Table 1 were then computed.

The quantities of water that percolated towards the well through each of the successive concentric cylindrical sections were computed from the formula Q = PIAT. For any particular section Q = the quantity of water in gallons a day, P = permeability, I = the slope of cone of depression, A = the area of the cylinder in square feet, and T = the period of pumping in days. The gradient I was obtained from Figure 1 by averaging the slope of the cone of depression up gradient and down gradient from the pumped well. A cylindrical section of water-bearing material with a radius of 50 feet was used as the control section. The quantities of water which percolated through the 50-foot cylinder were always greater than the quantities of water which percolated through successive larger cylinders because a certain amount of water passed through the 50-foot cylinder which was derived from the unwatering of the material between that cylinder and the larger cylinders. Each value of specific yield was obtained by computing the difference between the quantity of water that percolated through the 50-foot cylinder and the quantity that percolated through a larger cylinder, and dividing this difference in quantity of water by the volume of material unwatered between the 50-foot cylinder and the larger cylinder.

As an illustration, the specific yield will be computed for the volume of sediments unwatered between two concentric cylinders during the last 12 hours of pumping. The inner cylinder has a radius of 50 feet and the outer cylinder a radius of 400 feet. The average slope of the cone of depression during the last 12 hours of pumping, as taken from Figure 1, was 2.59 per cent at 50 feet from the pumped well and 0.213 per cent at 400 feet from the pumped well. The quantity of water that percolated through the 50-foot cylinder in the last 12 hours of pumping may be computed by substituting the proper values in the above formula. This formula then becomes Q = 700 × 0.0259 × 3.1416 × 100 × 97.5 × (12/24) = 276,000 gallons = 36,900 cubic feet. The quantity of water which percolated through the section with the radius of 400 feet was Q = 700 × 0.00213 × 3.1416 × 800 × 99.5 × (12/24) = 186,000 gallons = 24,900 cubic feet. The difference between the quantities of water that percolated through the two cylinders

of course is equal to 12,000 cubic feet. The volume of material between the cylinders which was unwatered in the last 12 hours of pumping, as computed from the decline of the water-table in that period, is 52,900 cubic feet. This quantity of 12,000 cubic feet of water came from the 52,900 cubic feet of sand and gravel between the two cylinders which were unwatered during the last 12 hours of pumping. The specific yield in this computation is therefore found to be 22.7 per cent (see Table 1).

The values of specific yield computed for different rings about the pumped well and for several periods are given in Table 1. The average value of specific yield determined from the last 12 hours of pumping is 24.8 per cent. A sample of the material which was unwatered during this test was examined in the hydrologic laboratory of the United States Geological Survey. The porosity of the sample was found to be 27.1 per cent and moisture-equivalent 2.6 per cent by volume. As the moisture-equivalent is sometimes used roughly for the specific retention, the specific yield of the sample was computed to be 24.5 per cent, which is nearly the same as the average value determined from this pumping-test.

Table 1--Specific yield as computed for several distances from the pumped well and for several periods after pumping began

Distances from pumped well	Period in hours after pumping began				
	2 to 6	6 to 12	12 to 24	24 to 36	36 to 48
feet					
50- 280	10.9	14.9	27.6	27.6	26.6
50- 320	9.9	13.6	25.9	26.6	28.3
50- 360	9.7	13.3	26.4	25.5	25.8
50- 400	9.5	12.9	25.0	24.6	22.7
50- 500	...	12.0	23.1	22.9	23.6
50- 600	...	14.3	23.1	23.8	22.8
50- 700	...	13.5	21.5	24.2	24.8
50- 800	...	13.3	20.1	22.6	24.7
50- 900	...	12.7	19.2	21.9	24.8
50-1000	...	....	18.1	20.4	23.4
Average	10.0	13.4	23.0	24.0	24.8

It will be noticed that the computed values for specific yield become larger as the time of pumping increases and smaller as the outer cylindrical section of the ring is chosen farther from the pumped well, the reason for these variations being that all of the water in a formation does not drain out of it immediately. Investigations have shown that a sample of material after being saturated will yield a very large percentage of its water within a few hours though it may continue to yield small amounts for several years (F. H. King, Principles and conditions of the movements of groundwater, U. S. Geol. Sur. Nineteenth Ann. Rep., pt. 2, pp. 86-91, 1899). When pumping first starts a comparatively large volume of sediments is unwatered, partly because only a small percentage of the water contained in the interstices of the sediments immediately drains down to the water-table. As pumping is continued more water gradually drains out of the unwatered sediments, and hence the values of specific yield computed from the volume unwatered during the first few hours of pumping are relatively small. The values computed for longer periods are more nearly the true specific yield of the materials. As shown in Table 1, the average value for specific yield increases but little after 24 hours of pumping. At any time after pumping starts the average time of draining of the unwatered volume is less than the period of pumping because the formation is unwatered by a progressive lowering of the water-table. The unwatered material close to the pumped well at any time has had a longer period of draining than the unwatered material farther from the pumped well. Thus it is to be expected that computed values of specific yield will decrease as the distance of the outer section of the ring from the pumped well is increased.

U. S. Geological Survey,
Washington, D. C.

DEEP-WELL SALINITY-EXPLORATION

A. G. Fiedler

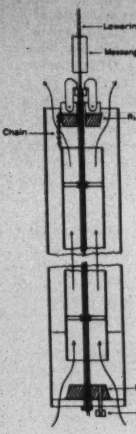


Fig. 1--Cross-section view of deep-well water-sampler

One of the outstanding accomplishments of recent years in connection with the study of the geologic source of ground-water and the quality of water yielded by different formations has been the development of methods and equipment for the exploration of wells. The description and use of the deep-well current-meter on well-exploration work in Hawaii and New Mexico has already appeared in published literature (John McCombs and A. G. Fiedler, Methods of exploring and repairing leaky artesian wells, U. S. Geol. Sur. Water-Supply Paper 596, pp. 1-32, 1928) on hydrology but recent developments in the application of electrical conductivity-measurements for determining the salinity of water in wells have not heretofore been presented. In addition to being of considerable scientific importance in connection with problems of ground-water hydrology, the practical value of locating the place at which salt water is entering a well and contaminating a potable water-supply is great. Such information may be the means of preventing the loss of large investments in industries, irrigation-projects, and cities that are dependent upon well-water supplies that may at some time become contaminated by salty or other highly mineralized water.

The method of determining the salinity of water by means of measuring its electrical conductivity is not a new idea, for the same principle has been applied in connection with the problem of measuring the salinity of sea-water and in determining the concentration of soluble salts in soils. The method was applied to the exploration of water-wells on the island of Oahu, Territory of Hawaii, in connection with an extensive survey of wells that was being made by the United States Geological Survey in cooperation with the Territory of Hawaii. However, the work did not go beyond the experimental stage, and the velocity-method which involves the use of the deep-well current-meter was continued as the chief method of exploration. The deep-well current-meter, which was designed especially for measuring velocities in wells, operates on the same general principle as the current-meter that is customarily used in gaging surface-streams. The electrical conductivity-method of exploring wells was demonstrated by Penn Livingston and Walter Lynch to be of practical value in the study of the salt-water problem in the Winter Garden Area in southwest Texas, which study was made in 1930 and 1931 by the United States Geological Survey in cooperation with the Texas Board of Water Engineers. It was upon this project that the method was developed for general practical use and applied upon an extensive scale.

Water that is essentially free from dissolved salts has a fairly high electrical resistance and hence a low conductivity, whereas salty water has a much lower resistance and hence greater conductivity. The purpose of the exploration is to determine the depths at which there is a marked increase in the conductivity, thereby indicating the points at which the mineralized water is entering the well.

The essential equipment consists of a Wheatstone bridge supplied by direct current from several standard dry-cell batteries and a pair of electrodes. The electrodes are attached to a special aeroplane strand-cable containing an insulated copper core and are lowered by means of a winch into the well that is to be explored. One electrode is grounded to the metal strands of the cable and the other is attached to the insulated core. The Wheatstone bridge-circuit is completed to the insulated core through a slip-ring and brush on the shaft of the winch and by a ground to the metal frame of the winch. The conductivity of the water across the electrodes submerged in the well is indicated by the measurement of the electrical resistance at various depths.

The original equipment was operated by direct current, but, because of variations in resistance that resulted from the polarization of the electrodes, new equipment composed of a slide-wire bridge, a balancing rheostat of 10,000 ohms capacity, and a microphone hummer operated by dry-cell batteries and supplying alternating current of

1,000 cycles was constructed for similar exploration-work in wells in Florida. With this equipment the circuit is in balance and indicates the resistance of the water across the electrodes when the slide-wire and resistances are so adjusted that a minimum hum is heard in a pair of head phones that are part of the electrical circuit.

As a check on the salinity indicated by the resistance-measurements, it has been found desirable to obtain samples of the water for chemical analysis at the points where a marked change in conductivity occurs. Water-samplers have therefore been devised to secure samples of water from any depth in either flowing or non-flowing wells. The water-sampler used in non-flowing wells consists of section of tubing which has leather flap-valves that operate on brass seats screwed in each end of the tube to prevent the escape of water within the sampler. Obviously a sampler of the flap-valve type is unsuited for use in flowing wells unless the sampler is removed from the well at a continuous rate that is in excess of the upward velocity of the flowing water for new water would enter the sampler and displace that which had been collected from below. A sampler having trip-valves that are operated by dropping a messenger-weight down the suspending cable was therefore designed and was used successfully on work in Florida. The general construction of this sampler is indicated in the diagram of Figure 1.

In exploring a well with the Wheatstone bridge-apparatus, the electrodes are lowered into the well and resistance-measurements are made at regular intervals. If a marked change in resistance is recorded, the electrodes are raised and additional readings are made at frequent intervals above and below the level at which the marked change occurred in order to determine fully the distribution of the salty water in the well. Samples of water are obtained with a deep-well water-sampler from depths at which marked changes in the character of the water are indicated. The chloride-content of the samples is determined in the field by the well-known volumetric method or by complete chemical analysis in the laboratory.

The accompanying graphs (Fig. 2) illustrate the pertinent data in regard to the distribution of salt water in a typical defective well which was explored in Texas. This well, which is 1,655 feet deep and 10 inches in diameter, was drilled in 1928. Definite information on the amount of casing in the well is not available. Water down to a depth of about 170 feet had a resistance of about 42 ohms. Between the depths of 170 and 178 feet the resistance decreased to 40 ohms, and in the next two feet it declined to 24 ohms. The resistance then continued uniform to a depth of 880 feet, and below that point gradually increased to 38 ohms.

It was concluded from the depth-resistance graph that highly mineralized water was entering the well at about 180 feet, and that this water was sinking because of its higher specific gravity and was filling the cased part of the well between 180 and 880 feet. It was further concluded that below 880 feet, which is apparently about the bottom of the casing, some of the highly mineralized water was washed out of the well and the rest was diluted by the fresher water from the water-bearing formation.

The graph showing the chloride-content of samples of water from the well substantiated these general conclusions. The well was filled with water containing about 1,500 parts per million of chloride to a depth of about 175 feet. The chloride increased abruptly within the next few feet and was 5,900 parts per million in the sample taken from the 185-foot level. The sample taken from a depth of 570 feet contained 4,650 parts per million of chloride which is 850 parts less than the amount found in the sample from 920 feet. Such a variation is to be expected for it is not likely that the salty water from above would displace uniformly the water from below that was left in the well at the conclusion of the last period of pumping. The interesting point to be noted in connection with the graph is that the chloride-content of the water-samples confirms the depth-resistance graph in indicating a very small diffusion-zone at the place where the salty water enters the well. Obviously such conclusive results in establishing the point of defect in the casing are of great value in connection with the problem of repairing the well.

In the salinity exploration-work in Sarasota County, Florida, that was done in 1932 by V. T. Stringfield of the United States Geological Survey, the deep-well current-meter mentioned previously was first used to explore the wells to determine if there was any leakage into or out of the wells and also to determine from what levels the wells were being supplied with water. In this area the wells are mostly 450 feet

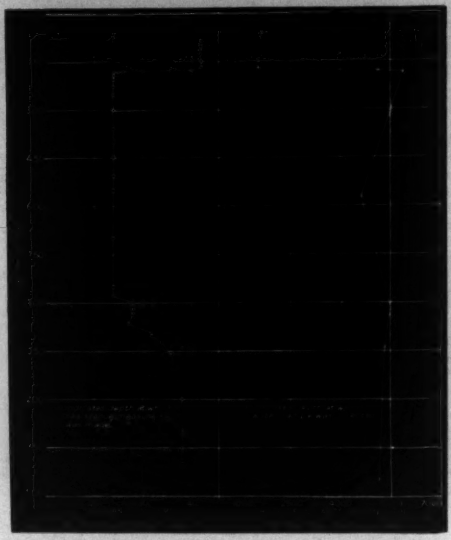


Fig. 2--Pertinent data, salt-water distribution, typical defective well, Texas

to 750 feet in depth and are cased for about 80 feet. The formations penetrated in the order named are the Hawthorn formation and the Tampa and Ocala limestones. The shallower wells end in the Hawthorn formation whereas those that are about 700 feet deep usually end in the Tampa limestone. Only a few of the deepest wells enter the Ocala limestone.

The tests with the current-meter showed that no water was coming from the bottom of the deeper wells and that the Ocala and Tampa limestones, which in some parts of the Peninsula are the most productive water-bearing formations, were yielding little or no water to the wells in that area. On the other hand, the tests indicated that the upper formation--the Hawthorn--was the principal water-bearer and that no leakage, which would tend to reduce the artesian pressure, was present.

Following the exploration with the deep-well current-meter, the resistance of the water was measured at regular intervals with the Wheatstone bridge-apparatus. The resistance of the water throughout the entire depth of the wells varied very little and showed only a small decrease from the top to the bottom—less than that which might have been attributed to temperature-changes. The conductivity-measurements indicated that saline water is present in the Hawthorn formation at a depth of 60 to 100 feet in several localities on the islands along the coast in the vicinity of Sarasota County and at a depth of 400 feet below the surface five miles east of the coast at Venice. Furthermore, it was found that salty water was present in the Tampa limestone at about 550 feet below the surface at Sarasota. The local distribution of this salt water is not definitely known but it is confined to coastal areas. It seems therefore to be related to the artesian head, which along the coast is in part due to the displacement of salt water by fresh water as explained by the "theory of Herzberg" (J. S. Brown, A study of coast ground-water, U. S. Geol. Sur. Water-Supply Paper 537, pp. 16-17, 1925). For reasons that can not be presented here, it is considered that some of the chloride-water may possibly be derived from connate or modified connate water.

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NOTES ON THE RELATION BETWEEN THE MOISTURE-EQUIVALENT AND THE SPECIFIC RETENTION OF WATER-BEARING MATERIALS

Arthur M. Piper

General statement

The moisture-equivalent and specific retention have been widely used as quasi-physical constants to measure the power of a water-bearing material or a soil to retain water against gravitative force. Comparatively little has been demonstrated, however, as to the relation of one to the other. This paper is a preliminary statement of the apparent relation between these two measures of retentive power and is based on a study of alluvial materials made in connection with an investigation by the United States Geological Survey into the ground-water resources of the Mokelumne Area, central California.

The moisture-equivalent, as introduced by Briggs and McLane (L. J. Briggs and J. W. McLane, The moisture-equivalent of soils, U. S. Dept. Agr. Bur. Soils Bull. 45, pp. 1-23, 1907) and subsequently modified by Briggs and Shantz (L. J. Briggs and H. L. Shantz, The wilting-coefficient for different plants and its indirect determination, U. S. Dept. Agr. Bur. Plant Industry Bull. 230, pp. 1-82, 1912), is the arbitrary ratio of (1) the weight of water which a soil, after saturation, will retain against a centrifugal force 1,000 times the force of gravity, to (2) the weight of the soil when dry. This ratio is commonly expressed by soil-scientists as a percentage of the dry weight of the soil, though it can as well be expressed as a percentage of the gross volume. Veihmeyer (F. J. Veihmeyer, C. W. Israelson, and J. P. Conrad, The moisture-equivalent as influenced by the amount of soil used in its determination, Calif. Univ. Agr. Exp. Sta. Tech. Paper 16, 65 pp., 1924; F. J. Veihmeyer, J. Oserkowsky, and K. B. Tester, Some factors affecting the moisture-equivalent of soils, First Internat. Cong. Soil Sci.--Washington, 1927--Proc. and Papers, v. 1, pp. 512-534, 1928) and his collaborators have shown that the moisture-equivalent is affected materially by differences in the technique of its determination but that if 30-gram samples are used and an adequate and standard technique is followed the determinations for a particular material agree within small limits of experimental error. Thus, arbitrary though the laboratory technique may be, it seems to measure relatively the power of the material to retain water, so far as that power is affected by the sizes of the constituent particles. It seems further that this relative measure is independent of the arrangement of the particles, as otherwise agreement between determinations would not be expected. Russell and Burr (J. C. Russell and W. W. Burr, Studies on the moisture-equivalent of soils, Soil Science, v. 19, pp. 251-266, 1925) have analyzed the dynamics of the moisture-equivalent determination and have shown further its arbitrary nature.

The specific retention of a water-bearing material is defined by Meinzer (O. E. Meinzer, Outline of ground-water hydrology, with definitions, U. S. Geol. Sur. Water-Supply Paper 494, p. 29, 1923) as the ratio of (1) the volume of water which, after being saturated, the material will retain against the force of gravity to (2) its own gross volume. This ratio by volume is commonly expressed by hydrologists as a percentage. It can as well be stated as a percentage of the dry weight of the material, and thus becomes analogous to the ordinary form of expressing the moisture-equivalent. The definition presumes that if the period of drainage is indefinitely long a condition of dynamic equilibrium is attained and that downward movement of water ceases. Further, the definition presumes conditions analogous to those which exist in the field, namely, that the communicating interstices of the material form capillary openings which extend indefinitely downward to a water-table and that the particular body or column of material considered is so far above the water-table that it lies in an equi-potential region with respect to the capillary and gravitational forces which control the distribution of moisture.

Two general methods of measuring the specific retention have been used: (1) Wetting and draining relatively small samples in the laboratory (Allen Hazen, Experiments upon the purification of sewage and water at the Lawrence Experiment Station, Mass. State Board Health, Twenty-third Ann. Rep., for 1891, pp. 428-434, 1892; F. H. King, Principles and conditions of the movements of ground-water, U. S. Geol. Sur. Nineteenth Ann. Rep., pt. 2, pp. 86-91, 1899) and determining their moisture-content after they have attained constant weight; (2) taking samples in the field (A. J. Ellis and C. H. Lee, Geology and ground-waters of the western part of San Diego County,

California, U. S. Geol. Sur. Water-Supply Paper 446, pp. 121-123, 1919) under conditions which satisfy the requirements for specific retention and determining their moisture-content. Neither method has been standardized. Commonly in the laboratory investigations a water-table or perched capillary-fringe has been maintained in the lower part of the sample; under such conditions the sample does not drain freely and thus may not indicate the specific retention. The results obtained from field investigations are dependent in large measure upon the judgment of the investigator unless many samples are taken over a period so long that the material is known to have drained completely. Commonly it is not feasible to do this and the results are correspondingly unsatisfactory.

Specific retention of alluvial materials from the Mokelumne Area, California

Experimental methods and results--In 1931 samples of 16 alluvial materials in the Mokelumne Area, central California, were taken in duplicate under the supervision of the writer for determination of the specific retention. Each sample was taken by digging a pit to the desired depth and—from a bench in the pit-wall—driving a cylinder of galvanized sheet-steel vertically into the material, forcing a steel plate beneath the cylinder to cut off the column of material, and then excavating the cylinder; thus, the natural arrangement of the grains was disturbed as little as possible. All but two of the materials were entirely incoherent; in them the cylinders were driven readily and the samples did not appear to be materially disturbed. The remaining two materials were compact, laminated silt; in these the cylinders were driven with difficulty and the sample was visibly cracked and somewhat brecciated at the top. The cylinders were six inches in inside diameter and 15 inches long; each was driven to a depth of 12 inches. Of the 16 pairs of samples, 13 were taken from one pit so as to constitute a pair of sample columns extending from the ground-surface to a depth of 13 feet; each of the remaining three pairs was taken from a separate pit. With each pair of samples, an additional portion of the material excavated from around the cylinders was preserved.

The samples were then transported to a covered observation-pit dug in sandy loam and coarse sand subsoil at Lodi, California. There, on benches in the wall of the pit, bottomless wooden bins about 6 inches deep were constructed and were filled with the additional portions of the 16 samples, these portions being compacted approximately to field density by wetting. On each bin so filled was placed the corresponding pair of cylinders containing the undisturbed samples, the metal base-plates having been replaced with 14-mesh copper screen-cloth soldered in place. Thus the undisturbed sample was in contact with the repacked sample in the bin and the repacked sample in turn was in contact with the sandy subsoil, so that essential continuity of the capillary openings was maintained between the samples and the water-table, which was about 20 feet below them. As the roof of the observation-pit was covered with about 10 inches of earth, the pit was maintained approximately at constant temperature and the diurnal fluctuation was generally only 1° or 2° F. Its atmosphere was also kept approximately saturated with water-vapor by maintaining two open vessels filled with water; thus the opportunity for evaporation from the samples was maintained at a minimum.

To the top of each cylinder thus set up, there was added water equivalent to about 25 per cent of the volume of the sample. Each sample was allowed to drain about ten days and was then wetted again (February, 1932) by removing it from its bin and placing it for 24 to 96 hours in a pan filled to a shallow depth with water. Thus, the second wetting was accomplished by capillary rise to avoid trapping air in the sample and to secure uniform distribution of the moisture. When the sample no longer would absorb water, as indicated by weighing, it was replaced on its bin and allowed to drain, the top of the cylinder being sealed with waxed paper pierced by one perforation made with a sharp pencil. Thus, evaporation was effectively prevented although atmospheric pressure was maintained at the top of the sample column. The rate at which the samples drained was determined by weighing them periodically, one or more times the first few days, then at progressively greater intervals. After 96 days (June, 1932) when the samples were losing weight but slowly, the distribution of moisture in one of each pair of the cylindrical samples was tested by taking three sub-samples from its axis, using a sampling tube about 0.9 inch in diameter and removing the top, middle, and bottom thirds separately. The moisture-content of the three axial sub-samples and of the remainder of the gross sample was then determined by

Table 1--Moisture-content and moisture-equivalent of axial samples from 6-inch specific-retention cylinders, series 2, after draining 96 days

(Quantities in per cent of dry weight of sample)

Pit and depth (feet below surface)	Retained moisture, R[a]	Moisture-equivalent, M[b]	Ratio, $\frac{R}{M}$	Pit and depth (feet below surface)	Retained moisture, R[a]	Moisture-equivalent, M[b]	Ratio, $\frac{R}{M}$
Woods-Wilhoit				Woods-Wilhoit (Continued)			
0 - 1[c]	13.4	11.4	1.18	8 - 9	6.8	5.5	1.24
	11.9	11.3	1.05		6.6	5.2	1.27
	14.3	12.0	1.19		5.9	4.2	1.40
1 - 2	12.6	11.3	1.12	9 - 10	5.5	2.2	2.50
	12.5	11.9	1.05		2.8	2.1	1.33
	14.2	13.0	1.09		14.8	17.1	0.87
2 - 3	12.4	12.0	1.03	10 - 11	13.9[d]	6.0	2.32
	12.7	12.0	1.06		19.3[d]	7.5	2.57
	14.0	12.5	1.12		24.8[d]	9.7	2.56
3 - 4	12.5	12.1	1.03	11 - 12	21.4[d]	7.2	2.97
	12.5	12.0	1.04		4.7	2.1	2.24
	14.4	12.6	1.14		4.8	2.5	1.92
4 - 5	13.7	12.9	1.06	12 - 13	4.4	3.0	1.47
	13.1	12.6	1.04		6.9	3.4	2.03
	14.9	15.5	0.96		4.8	3.2	1.50
				La Lomita, irrigated			
5 - 6	21.3	23.8	0.90	12 - 13	34.0	[e]	
	23.6	27.2	0.87		32.3	[e]	
	24.0	26.4	0.91		32.3	[e]	
				La Lomita, non-irrigated			
6 - 7	19.2	20.0	0.96	6.6 - 7.6	10.6	7.5	1.41
	12.1	11.0	1.10		11.4	7.9	1.44
	16.7	15.6	1.07		12.9	8.8	1.47
				Inglis			
7 - 8	20.8	20.9	1.00	8 - 9½	31.3	32.9	0.95
	22.9	24.4	0.94		31.2	31.8	0.98
	14.6	16.5	0.89		32.5	33.7	0.96

a) Moisture-determinations by C. A. McClelland, U. S. Geological Survey.
b) Moisture-equivalent determinations by A. Rizzi, College of Agriculture, University of California. c) Data from top, middle, and bottom thirds of each 1-foot sample indicated by relative order in the table. d) Not plotted in Figures 1-3. e) Not yet determined.

standard methods in the field laboratory of the United States Geological Survey at Lodi. Subsequently the moisture-equivalent was determined on the oven-dried subsamples and on a representative part of the gross sample, also oven-dried. The determinations of moisture-equivalent were made by Aldo Rizzi in the Irrigation Laboratory of the College of Agriculture, University of California, at Davis, California. They were made according to the standard technique developed by Veihmeyer (F. J. Veihmeyer, op. cit., 1924 and 1928) and under his supervision. The experimental data from the small axial samples are given in Table 1.

The moisture-content of each of the 16 gross samples exceeded the average moisture-content of the corresponding three axial sub-samples, though the excess was less than five per cent of the content in four samples and less than ten per cent in

six other samples. One of the gross samples contained about one and a half times as much water as the corresponding three axial samples. These relations imply that after the cylinders had drained 96 days, the retained moisture was not uniformly distributed and was appreciably less in the axial portion of a majority of the cylinders. The unequal distribution may have been due in part to differences in mechanical composition from place to place in the undisturbed samples.

The remaining set of the initial pairs of samples continued to lose weight at a gradually decreasing rate and was allowed to drain approximately one year, by which time the rate of loss had become very small. The amount and distribution of their retained moisture is now (March-April, 1933) being determined. Incomplete data from seven of these samples are now available and suggest that after the cylinders have drained about a year the retained moisture is much more uniformly distributed across any particular transverse section and that the moisture-content of the whole sample differs but little from that of the axial sub-samples taken after 96 days of drainage.

Relation between moisture-equivalent and specific retention

It is believed that the experimental conditions maintained in the investigation at Lodi have satisfied rather effectively the theoretical requirements for a determination of the specific retention, and that the specific retention of the alluvial materials studied is measured approximately by the moisture-content of the sub-samples from the axes of the cylinders after 96 days of drainage.

Figure 1, which is based on the data presented in Table 1, defines within considerable limits of error a systematic relation between the moisture-equivalent and the retained moisture or specific retention. This systematic relation seems to obtain even though the samples are not all uniform in texture, as is indicated by a moderately wide range in the moisture-equivalent of the three sub-samples taken from several of the cylinders. Clearly, the specific retention and moisture-equivalent are not equal throughout the range of the experimental data. The ratio of the specific retention to the moisture-equivalent is not far from unity for moisture-equivalents between about 12 and 34 per cent of the dry weight of the material, and as the curve is drawn in Figure 1 the ratio is unity at about 17 per cent. For moisture-equivalents less than 12 per cent the ratio increases more or less progressively. None of the materials tested had moisture-equivalents greater than 34 per cent or less than 2 per cent.

Relation between specific retention and field-capacity

A property of soils analogous to the specific retention is expressed by students of soil and irrigation as the field-capacity, or, as it is also termed, the field-carrying capacity, field-water capacity, and water-retaining capacity. The field-capacity is generally accepted to be the moisture-content of the soil a short time (usually between one and five days) after water from rainfall or irrigation has disappeared from the surface, provided that (1) the soil drains freely and is free from pronounced discontinuities in texture, (2) losses by transpiration or evaporation are relatively small, and (3) downward movement of water has practically ceased (A. H. Hendrickson and F. J. Veihmeyer, Irrigation experiments with peaches in California, Calif. Univ., Agr. Exp. Sta. Bull. 479, p. 4, 1929). It is generally expressed as a percentage of the dry weight of the soil but is transposed readily to a percentage by volume by multiplying by the apparent specific gravity of the dry soil. It is measured by determining the moisture-content of soil-samples collected when the requirements for field-capacity have been satisfied. Unless samples are taken at several different intervals after the rainfall or irrigation, the validity of the results depends largely upon the judgment of the investigator as to (1) the adequacy of the rainfall or irrigation to replenish the deficiency in soil-moisture, (2) the lapse of time after irrigation necessary for the absorbed water to become uniformly distributed in the soil and to cease appreciable downward movement, (3) the losses by evaporation and transpiration in the interim, and (4) the depth to which samples should be taken. Commonly the depth of the water-table below the surface is not reported or is disregarded by the investigator, although it is a useful index of the capillary potential within the depth of sampling.

In Figure 2 the graph of the ratio R/M is compared with the data reported by several workers who have studied the relation between the moisture-equivalent and the

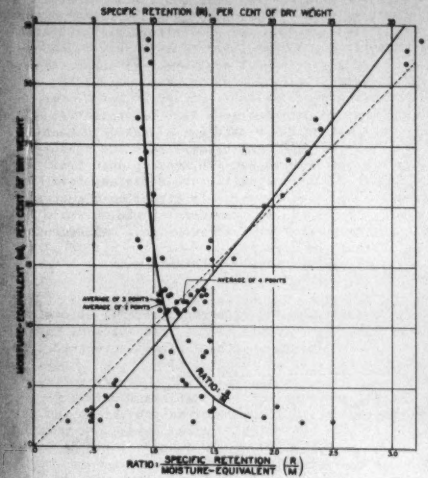
SPECIFIC RETENTION (R), PER CENT OF DRY WEIGHT
MOISTURE-EQUIVALENT (M), PER CENT OF DRY WEIGHT
AVERAGE OF 4 POINTS
AVERAGE OF 3 POINTS
AVERAGE OF 3 POINTS
RATIO
RATIO: SPECIFIC RETENTION / MOISTURE-EQUIVALENT (R/M)

Fig. 1--Relation of moisture-equivalent to specific retention

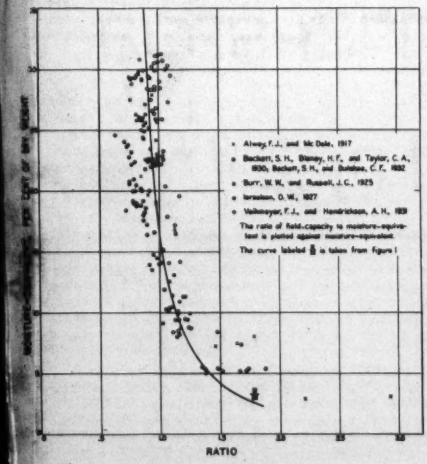
MOISTURE-EQUIVALENT (M), PER CENT OF DRY WEIGHT
Alway, F. J., and Mc Dole, 1917
Beckett, S. H., Blaney, H. F., and Taylor, C. A., 1930; Beckett, S. H., and Dunshee, C. F., 1932
Burr, W. W., and Russell, J. C., 1925
Israelsen, O. W., 1927
Veihmeyer, F. J., and Hendrickson, A. H., 1931
The ratio of field-capacity to moisture-equivalent is plotted against moisture-equivalent.
The curve labeled R/M is taken from Figure 1
RATIO

Fig. 2--Relation of field-capacity to moisture-equivalent and specific retention

field-capacity of agricultural soils. Thus Veihmeyer and Hendrickson (F. J. Veihmeyer and A. H. Hendrickson, The moisture-equivalent as a measure of the field-capacity of soils, Soil Science, v. 32, pp. 183-184, 1931) report the moisture-equivalent and field-capacity of 19 agricultural soils, the moisture-equivalents ranging from 14 to 27 per cent of the dry weight. Dr. Veihmeyer has kindly furnished to the writer unpublished data indicating the field-capacity and moisture-equivalent of five additional soils to a depth of 48 inches; the moisture-equivalent of these ranges from 31 per cent down to 5 per cent. These published and unpublished data define a curve of the same general form as that shown in Figure 1 but throughout its length it lies somewhat to the right, that is, in the region of greater retained moisture. In the range of moisture-equivalents between 30 and 8 per cent the difference between the two curves is but little more than the probable experimental error; for moisture-equivalents less than 8 per cent the curves appear to diverge more widely but the data are not adequate.

Beckett and his collaborators (S. H. Beckett, H. F. Blaney, and C. A. Taylor, Irrigation-water-requirement studies of citrus and avocado trees in San Diego County, California, 1926 and 1927, Calif. Univ. Agr. Exp. Sta. Bull. 489, pp. 14-44, 1930; S. H. Beckett and C. F. Dunshee, Water requirements of cotton on sandy loam-soils in southern San Joaquin Valley, Calif. Univ., Agr. Exp. Sta. Bull. 537, pp. 9, 22, 1932) report data from which the writer has estimated the field-capacity of 22 soil-materials whose moisture-equivalents are reported to range between 7.5 and 15 per cent. These data are unsatisfactory in that they comprise relatively few determinations of moisture-equivalent and those not on the samples taken to ascertain the moisture-content. All but two of the points plotted from Beckett's data on Figure 2 agree reasonably well with the curve of the ratio R/M; the two discordant points lie well within the region of greater retained moisture.

To the tops of cylindrical samples of 16 soils, Alway and McDole (F. J. Alway and G. R. McDole, Relation of the water-retaining capacity

of a soil to its hygroscopic coefficient, J. Agr. Res., v. 9, pp. 65-66, 1917) applied water equal to a depth of one inch, protected the cylinders against evaporation, allowed them to stand five days, and then determined the moisture-content and moisture-equivalent of the upper two or three inches of the soil-column. The moisture-equivalents ranged between about two and 30 per cent. When these data, which are presented graphically, are transposed to the diagram (Fig. 2), they agree closely with the curve of the ratio R/M in the range of moisture-equivalents between 30 and 18 per cent. In the range of moisture-equivalents from 18 per cent down to two per cent, Alway and McDole found progressively more retained moisture than is indicated by the curve of the ratio R/M; with a moisture-equivalent of two per cent, they found about six per cent of moisture. These investigators also wetted and drained repacked cylindrical samples of a medium-grained soil under conditions similar to those maintained in the investigation in the Mokelumne Area. The cylinders were six inches in diameter, were filled to a depth of 30 inches, and were drained 31 to 126 days. Those which were drained 96 days and longer appeared to have reached equilibrium, the final average moisture-content of the samples being reported as 13.8 per cent and the moisture-equivalent as 13.5 per cent. For this moisture-equivalent the Mokelumne samples showed a slightly larger moisture-content.

Burr and Russell (W. W. Burr and J. C. Russell, Report of certain investigations on the central Nebraska Irrigation Project, Neb. Dept. Public Works, Biennial Rep. for 1923-1924, pp. 226-230, 1925) and Israelson (O. W. Israelson, The application of hydrodynamics to irrigation and drainage problems, Calif. Univ., Hilgardia, v. 2, pp. 508-518, 1927) have investigated the capacity of soils to retain water after excessive irrigation and long periods of drainage. Their results are of considerable interest for comparison with determinations of field-capacity made after a relatively brief period of drainage.

Burr and Russell, working on loose soils in central Nebraska, flooded experimental plats at six different localities, mulched them to minimize evaporation, and accepted the moisture-content of the soil after the lapse of 68 days as indicating the ultimate field-capacity. They report moisture-equivalent and field-capacity of each one-foot layer of the soil to a depth of six feet. Of these data, those representing the depths four to six feet are plotted on Figure 2; the data representing the topmost two feet were discarded by the writer as possibly not measuring the field-capacity because as much as 0.82 inch of rain fell on the plats in the ten days prior to the final sampling. The moisture-equivalents in the soils from these plats range only from 22.5 to 30 per cent. Within this range, the data of Burr and Russell agree approximately with the curve of R/M but lie to the left of that curve, that is, in the region of less retained moisture (Fig. 2).

Israelson, working on uniform loam-soil near Logan, Utah, where the water-table was about 50 feet below the surface, enclosed three plats 38 feet long and 33 feet wide with levees and irrigated them excessively by adding water equal to a depth of inches, 24 inches, and 36 inches, respectively. The plats were then covered with a mulch of straw and allowed to drain, samples for the determination of moisture-content being taken to a depth of 12 feet at unequal intervals over a period of 120 days. The evaporation from the surface of the plats was measured with an evaporimeter-pan and corrections for this loss were applied. It was concluded that the moisture-content of the soil after the lapse of 69 days approached closely to equilibrium. Israelson indicates the moisture-content and moisture-equivalent of the soil by diagrams, the range in moisture-equivalent being only from 15 to 25 per cent of the dry weight of the soil. These data, which the writer has transposed to Figure 2, indicate appreciably less retained moisture than would be computed from the curve of R/M.

Several others, whose work has been summarized by Veihmeyer and Hendrickson (F. J. Veihmeyer and A. H. Hendrickson, op. cit., p. 182), have investigated the relation between the moisture-equivalent and the field-capacity of agricultural soils. Unfortunately, much of this work has been based on the average of many determinations of moisture-content supported by relatively few determinations of moisture-equivalence. The effect of this disproportion in the two determinations is to mask the true relation between them. Accordingly, the data are unsatisfactory for close comparison with the curve of R/M.

The data reported by Alway and McDole, Veihmeyer and Hendrickson, Beckett and his

collaborators, Burr and Russell, and Israelson, when plotted together on Figure 2, fall in a zone which has the same general form as the curve of R/M and which is approximately bisected by that curve in the region of moisture-equivalents between 34 and 8 per cent. In the region of moisture-equivalents less than 8 per cent, the zone of plotted points falls above and to the right of the curve of R/M, that is, in the region of greater retained moisture. In considerable part, the range in the position of the plotted points may be due to differences in the technique of the several investigators in determining the moisture-equivalent.

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REVIEW OF THE THEORY OF TURBULENT FLOW AND ITS RELATION TO SEDIMENT-TRANSPORTATION

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In flowing streams the percentage of suspended material decreases with distance above the bed and, with a certain depth and average velocity, particles above a critical size or specific gravity are not put into suspension. As the random velocities which make up the turbulent flow (turbulent flow as distinguished from laminar or viscous flow) also provide the means for carrying the particles into the interior of the fluid, a quantitative theory of turbulent-flow should also provide a theory for distribution of material in suspension. The present paper is a review of the theory of turbulent flow developed by Osborne Reynolds, Prandtl, von Karman, and Taylor, and of its application to the distribution of suspended material by Schmidt and others.

Shearing force and mechanical viscosity--During steady flow in a circular pipe, the shearing force per unit-area over a cylindrical surface at radius r is obtained from the equilibrium-equation

$$\tau = \frac{r}{2} \cdot \frac{dp}{dx} \qquad (1)$$

Here τ is the average shearing-force, p is the pressure, and x is the distance in the direction of motion. If the flow is laminar, the relation between the shearing force and the velocity-gradient is

$$\tau' = \mu \frac{du}{dr} \qquad (2)$$

where μ is the viscosity, a property of the fluid itself. If it is assumed that a similar equation applies to turbulent flow, a quantity corresponding to μ can be computed from measured pressure- and velocity-gradients, but this coefficient will not depend on the kind of fluid alone, but on the manner of flow as well. The defining equations are

$$\tau = \varepsilon \cdot \frac{du}{dr} = \frac{r}{2} \cdot \frac{dp}{dx} \qquad (3)$$

$$\varepsilon = \frac{r}{2} \cdot \frac{dp/dx}{du/dr} \qquad (4)$$

The quantity ε has been referred to by various writers as the mechanical viscosity, eddy-viscosity, and eddy-conductivity. German writers refer to it as the "Austauschkoeffizient."

Application of this line of reasoning to the steady flow of water in an open channel immediately leads to difficulty because the maximum velocity is often found at a point some distance below the surface and, on the basis of pipe-flow, it would appear that the free surface exerts a shearing force proportional to the area of the channel above the line of maximum velocity. The distribution of shearing force given by Leighly (J. B. Leighly, Toward a theory of the morphologic significance of turbulence in the flow of water in streams, Univ. Calif. Pub. Geog., v. 6, No. 1, 1932) assumes this to be the case. The depression of the maximum velocity below the surface has been explained on the basis of secondary spiral motions, but to the writer this explanation does not appear to be mechanically sound.

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If we consider a wide channel of depth D, the shearing force at a distance y above the bottom is usually expressed as

$$\tau = \gamma(D - y)s$$

where γ is the unit weight and s is the slope. Introducing the mechanical viscosity, as in the case of pipe-flow

$$\tau = \varepsilon \cdot \frac{du}{dy} \tag{5}$$

$$\varepsilon = \frac{\gamma(D - y)s}{du/dy} \tag{5a}$$

At the point of maximum velocity, $\frac{du}{dy} = 0$ and ε must become infinite unless the shearing force vanishes simultaneously. In order that the shearing force be zero at this point, the surface must exert a retarding force equal to $\gamma(D - y_m)s$, where y_m is the corresponding depth.

Shearing force and momentum-transfer--The apparent shearing-force on an area parallel to the bottom of the channel can be related to the transfer of momentum across the area in much the same way that the equation for the viscosity is developed in the kinetic theory of gases. The velocity at a point at any instant is assumed to be made up of the average velocity u in the direction of motion and fluctuating velocities u' and v' in both the forward and transverse directions. From the definition of the average velocity, the average values of u' and v' at a point are zero over a sufficiently long time, T, and at a certain instant are zero over a sufficiently large area, A. These relations are expressed by

$$\frac{1}{T}\int_0^T u'dT = \frac{1}{T}\int_0^T v'dT = \frac{1}{A}\int_0^A u'dA = \frac{1}{A}\int_0^A v'dA = 0 \tag{6}$$

The average velocity u would be measured by a frictionless current-meter following the velocity-fluctuations in the x-direction exactly.

Considering two-dimensional flow, the rate of transfer of x-momentum across a horizontal area, A, at y = constant is

$$\rho \int_0^A (u + u')v'dA$$

The apparent retarding force on a layer of thickness dy is equal to the net loss of momentum and is

$$\rho \left[\frac{d}{dy}\int_0^A (u + u')v'dA\right]dy$$

The effect is the same as if a shearing force were applied with a distribution given by the relation

$$A\frac{d\tau}{dy}dy = \rho\left[\frac{d}{dy}\int_0^A (u + u')v'dA\right]dy$$

or

$$\frac{d\tau}{dy} = \frac{\rho}{A} \cdot \frac{d}{dy}\int_0^A (u + u')v'dA \tag{7}$$

But from (6)

$$\frac{1}{A}\int_0^A (u + u')v'dA = \frac{1}{A}\int_0^A u'v'dA$$

Representing the average value of the product u'v' over the area A by $(u'v')_m$ and integrating (7), the apparent shearing-force is

$$\tau = \rho(u'v')_m \tag{8}$$

The assumption made by Prandtl is that each particle retains its original momentum during its transverse motion until it reaches its new position, where it mixes with the surrounding fluid and takes on the corresponding average velocity. If the average transverse distance travelled is ℓ, the value of u' can be expressed by the series

$$u' = \ell \frac{du}{dy} + \frac{\ell^2}{2} \frac{d^2u}{dy^2} + \cdots$$

If ℓ is small, the first term will suffice. Substituting this value in (8), the shearing force at any y is

$$\tau = \rho (v' \ell \frac{du}{dy})_m$$

But $\frac{du}{dy}$ is constant over the horizontal area considered and the equation becomes

$$\tau = \rho \frac{du}{dy} (v' \ell)_m \qquad (9)$$

Comparison with equation (5) gives as the expression for the mechanical viscosity

$$\varepsilon = \rho (v' \ell)_m \qquad (10)$$

Prandtl (L. Prandtl, Neuere Ergebnisse der Turbulenzforschung, Zs. V.D.I., Bd. 77, Nr. 5, Feb. 4, 1933) further assumes that v' is proportion to u' and obtains the expression

$$\tau = \rho \ell^2 \left| \frac{du}{dy} \right| \cdot \frac{du}{dy} \qquad (11)$$

From a consideration of the conditions for similarity at a point, von Karman (Th. von Karman, Mechanische Ähnlichkeit und Turbulenz, Proc. 3d. Int. Cong. Applied Mech., Stockholm, 1930) finds that the average transverse distance ℓ is

$$\ell = K \left| \frac{du/dy}{d^2u/dy^2} \right| \qquad (12)$$

and the shearing force

$$\tau = \rho K^2 \frac{(du/dy)^3}{(d^2u/dy^2)^2} \cdot \left| \frac{du}{dy} \right| \qquad (13)$$

where K is a universal constant, stated by Tollmien (W. G. Tollmien, The present state of the turbulence-problem, A.S.M.E. Applied Mechanics, v. 1, No. 1) to be about 0.4. Equation (12) permits a computation of ℓ and K from measured velocity-distribution curves and hence of the average value of $|v'|$. Both equations (11) and (13) make the shearing force zero at the point of maximum velocity and, if they are correct, indicate that a shearing force is applied above this level. G. I. Taylor (G. I. Taylor, Eddy-motion in the atmosphere, Trans. R. Soc. A, No. 215, 1915) obtained an equation similar to (9) by assuming that during the transverse motion the vorticity of each element remains constant until the new position is reached.

Distribution of suspended material--The cross-currents or eddies which transfer momentum and result in an apparent shearing-force, also provide the mechanism for distributing suspended material throughout the interior of a fluid. The material in suspension falls relative to the fluid surrounding it but this effect is compensated by the transfer of material through eddy-motion. Assuming that the average percentage of sediment decreases with distance above the bed, the upward velocities will carry with them more sediment than is returned by the downward velocities and thus it is possible to attain a distribution of sediment which is steady. The theory which follows is based largely upon Taylor (see reference above) and Schmidt (W. Schmidt, Die Massenaustausch in freien Luft und verwandte Erscheinungen, H. Grand, Hamburg, 1925).

If m_0 is the average concentration of sediment at some initial position y_0, the average concentration m at any other elevation y is

$$m = m_0 + (y - y_0) \frac{dm}{dy} + \frac{1}{2} (y - y_0)^2 \frac{d^2m}{dy^2} + \cdots$$

If fluid starts from the position y_0 and penetrates an area A at y = constant, the rate at which sediment crosses this area at any instant is

$$\int_0^A v' m_0 dA = m \int_0^A v' dA + \int_0^A v' (y_0 - y) \frac{dm}{dy} dA \qquad (14)$$

where only the first term of the series has been retained. From (6), $\int_0^A v'dA = 0$ and $\frac{dm}{dy}$ does not vary over the area A so that

$$\int_0^A v'm_o dA = \frac{dm}{dy}\int_0^A v'(y_o - y)dA \tag{14a}$$

following the same line of reasoning, the rate at which sediment crosses an equal area at elevation (y + dy) is

$$(\frac{dm}{dy} + \frac{d^2m}{dy^2}dy)\int_0^A (v' + \frac{dv'}{dy}dy)(y_o - y)dA \tag{14b}$$

Assuming that the term $\frac{dv'}{dy}$ is small, the rate at which sediment is carried into a layer of thickness dy by the turbulent motion is

$$\frac{d^2m}{dy^2}dy\int_0^A v'(y_o - y)dA \tag{15}$$

The rate at which the sediment moves downward out of the same lamina is

$$-ACm + AC(m + \frac{dm}{dy}dy) = AC\frac{dm}{dy}dy \tag{16}$$

where C is the velocity of fall in still water of the particular size under consideration. The absolute vertical velocity of the silt at any instant is (v' - C) and the average value over an area A is

$$\frac{1}{A}\int_0^A (v' - C)dA = -C \tag{17}$$

so that the use of the velocity of fall in still water is justified in (16).

Combining equations (15) and (16), the equation for the distribution of sediment is

$$C\frac{dm}{dy} = \frac{1}{A}\frac{d^2m}{dy^2}\int_0^A v'(y_o - y)dA \tag{18}$$

On the average, the eddies carrying the sediment originate at a distance ℓ above and below the plane under consideration and the average value of the product $v'(y - y_o)$ is $(v'\ell)_m$, just as in the case of the momentum-transfer. Inserting this value in (18) and integrating

$$Cm + (v'\ell)_m\frac{dm}{dy} = \text{constant}$$

The constant of integration is zero since $\frac{dm}{dy} = 0$ if $m = 0$. Replacing $(v'\ell)_m$ by (ε/ρ) from equation (10), the equation for the distribution of suspended material corresponding to a particular value of C is

$$Cm + (\frac{\varepsilon}{\rho})\frac{dm}{dy} = 0 \tag{19}$$

If the distribution of sediment of a certain size and its velocity of fall in still water are measured, the quantity (ε/ρ), and hence the mechanical viscosity ε, can be computed from equation (19). The theory requires that m decrease continuously from the bed upwards if ε is to remain finite. Curves of sediment-distribution in the Missouri River at Kansas City (L. G. Straub, Trans. Amer. Geophys. Union, Section of Hydrology, 1932) show this relation, except for fine silt and this discrepancy may be attributable to observational errors. In general, m does decrease uniformly and ε is a continuous function of y between the bed and the surface. Equation (19) is integrable if ε can be expressed as a function of y.

The value of ε given by equation (5a) is supposedly identical with that of equation (19) and a comparison of these values obtained from simultaneous measurements of the distribution of velocity and suspended material will provide a check on the theory of turbulent flow. The two are certain to disagree between the point of maximum velocity and the free surface for reasons already mentioned but throughout the remainder of the

depth, the difference between the two values should be small except immediately below the point of maximum velocity. Unfortunately simultaneously observed velocity- and silt-distributions are not available for making this comparison. Laboratory equipment for this work is expensive and the results obtained in the laboratory would probably not be as satisfactory as field measurements.

Conclusions--The most important result from a theoretical standpoint is the possibility of checking the theory of turbulent flow by simultaneous measurements of sediment-distribution and average velocity at each depth. The difficulty of measuring the fluctuating components of velocity is greater than that of measuring the average concentration of sediment and it appears possible to obtain information regarding the fluctuating velocities without measuring them. It is unfortunate that the product $(v'\ell)_m$ enters both equations since it makes it impossible to obtain the value of either $/v'/$ or $/\ell/$ independently.

A practical application of the theory, if it is verified experimentally, lies in the computation of the total volume of sediment carried in suspension. The average velocity at a point can be measured more easily than the percentage of sediment, since a mechanical analysis is involved as well as the sampling. A knowledge of the distribution of sediment could be obtained from a single measurement of the silt-content and a curve of the distribution of velocity. The curve of silt-content could be worked out from equation (19) from the bottom to a point just below the thread of maximum velocity and extrapolated from this point to the surface.

Nothing has been said as to how the sediment is picked up from the bottom and placed in suspension as the theory of turbulent flow is probably not valid in this region. In the case of pipe flow, both ℓ and v' are zero at the walls and increase with distance from it but in a stream vertical velocities may exist at the bed, which are capable of lifting solid material. However, it is entirely possible that the velocity-gradient rather than the actual velocity determines the motion of the bed. The theory outlined will give some information regarding the percentage of sediment as close to the bed as velocity-measurements can be carried.

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BED-SEDIMENT TRANSPORTATION IN OPEN CHANNELS

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The laws governing sediment-transportation are receiving more and more attention from hydraulic laboratories and hydraulic engineers, as a knowledge of them is fundamental to both river-models and river-construction work. These require two distinct applications of the same principles. In river-models a sediment must be used which will respond to the flow in such a manner that geometrical similarity is maintained, whereas in river-work the cross-sections must be designed to suit the sediment from which they are composed. In both cases the same laws are applicable.

Up till recently both these problems have been attacked by the use of methods drawn from experience, but with varying success. It has become evident that a knowledge of the principles of sediment-transportation is necessary. Observation of natural channels as well as theoretical considerations have failed to yield dependable conclusions. The only way out is to take the problem into the laboratory and there to dissect it under controlled conditions. G. K. Gilbert realized this many years ago, but in spite of a valiant effort the results of his work (Prof. Paper 86, U. S. Geol. Sur., 1914) do not give more than a general conception of sediment-laws. Other experimenters in Europe took up the work, but they have, for the most part, worked with sands and gravels of uniform grain-size. As such do not occur in nature, this work is not immediately applicable, as it has been demonstrated that a mixture will behave quite differently from a sand of uniform grain-size even though the mean grain-sizes are the same.

In Berlin, Kramer experimented with sand-mixtures (Modellgeschiebe und Schleppkraft, Mitt. Preussischen Versuchsanstalt für Wasserbau und Schiffbau, Heft 9, Berlin,

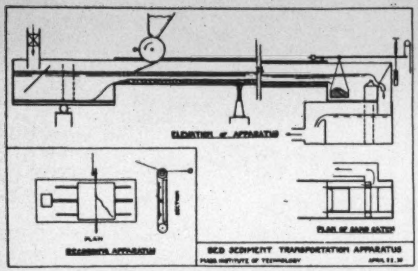

Fig. 1

1932) with the express purpose of finding those properties which must be considered in building river-models. He developed an equation which gives the initial tractive-force at which a sand-mixture will begin moving. This was a valuable contribution and has paved the way toward the solution of the more general problem.

To continue the laboratory attack on the sediment-laws, the writer constructed an apparatus in the River Hydraulic Laboratory of the Massachusetts Institute of Technology. It consisted of a 32-foot tilting flume equipped with an automatic sand-feeding device, a chronographic recorder for the sand-discharge and the means for controlling the slope, depth, and discharge of the water. In order to avoid any error due to the retardation of the water along the walls of the flume, the lower end of the flume was split into three sections by longitudinal plates so that the sand and water from the central section could be measured separately while the flow along the sides was wasted (Fig. 1).

A systematic program of research was planned to investigate a series of synthetic sand-mixtures, each within as wide a range of flow-conditions as possible. The ultimate goal of these studies is the possibility of predicting the sediment-movement of any sand-mixture under any flow-conditions from a knowledge of a mechanical analysis of the sand. This work is still in progress, but enough has been completed to indicate the general nature of the transportation-laws.

In the Gilbert experiments the water-discharge and the rate of sand-feed were kept constant until a state of equilibrium of the slope was reached. Then the bed-slope, depth, and sand-discharge were measured. In most cases the surface-slope was not recorded and the duration of the sand-measurement was very short—frequently less than five minutes. This method allowed considerable error and it is not surprising that the experiments were inconclusive.

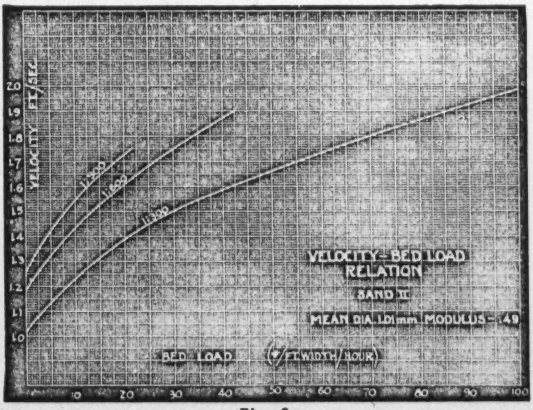

Fig. 2

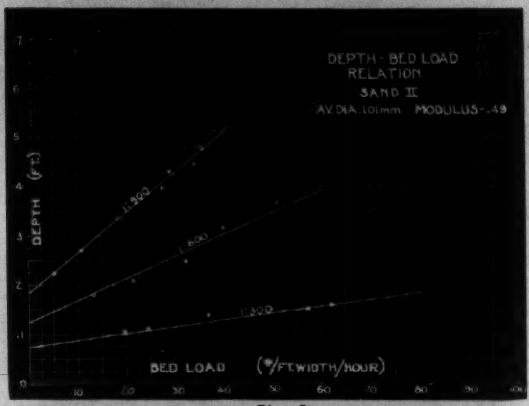

Fig. 3

Fig. 4

To avoid these difficulties, the procedure adopted at Massachusetts Institute of Technology kept the flow and slope constant while sand was added at the upper end of the flume at such a rate that the bed-level remained constant. With this method an illusive equilibrium does not have to be reached, but all factors are kept the same throughout the run. The recording apparatus provides a mass-curve of the weight of sand discharged. The slope of this line is then the average rate of sand-discharge for the run. The whole success of the experiment depends upon the precision with which individual factors can be controlled and consequently the design of the apparatus is of the first importance.

Much has yet to be learned about the progressive phases in the phenomenon of sediment-movement. Briefly enumerated they are as follows in the order in which they occur as the discharge through a channel is increased.

(1) Flow without sediment-movement.
(2) Movement in a uniformly distributed layer. This begins at a definite stage when the tractive force (measured by the product slope × depth or slope × discharge) reaches a certain value.
(3) Movement in riffles which travel downstream. This also begins at a critical tractive force whose value has yet to be defined. The riffles develop in size as the discharge increases until the fourth stage begins.
(4) Uniformly distributed movement or movement in which the riffles are not parallel to the water-surface but the riffle-crests are beneath the wave-troughs. This movement begins near the critical stage where the flow changes from streaming to shooting, but it has not otherwise been clearly defined.
(5) Anti-dune movement in which the riffles move against the current. It occurs only in shooting flow and is rarely observed.

Of these five phases of sediment-movement, only the first three are at present of practical importance. In river-model work the third phase must be subdivided as a point is reached in the riffle-development where the riffles have grown to such a size that the friction-coefficient of the channel is abruptly changed and the flow badly distorted. This point is called the "upper limit" by Kramer.

The relation of these various phases of transportation to the sand- and flow-factors has yet to be determined, but one fortunate fact has emerged. The amount of sand moved is independent of the type of movement. In other words, there is no break in the sediment-discharge curve as it passes through the various phases of movement. The bed-load is strictly a function of the tractive forces which may be expressed as the product of the slope × depth or of the slope × discharge. It is probably a function of the velocity-gradient at the bed which cannot be measured, but it cannot be expressed in terms of the mean channel-velocity only.

The equation-form which has been found to fit accurately the data already accumulated at Massachusetts Institute of Technology is as follows

$$G = A\, s^B\, (sq - C)$$

where G = bed-load in lbs/ft width/sec, s = slope, q = discharge in cu ft/ft width/sec. A and B are constants dependent only upon the specific gravity and mechanical composition of the sand. $C = sq_o$, where q_o is the initial discharge at which the sand begins moving. C is also a sand-constant and is independent of the relative values of s and q_o.

The above equation has been found to fit data gathered by Gilbert on sand-mixtures. It also applies to uniform-grain sands tested by Schoklitsch (Geschiebebewegung in Flüssen und an Stauwerken, Springer, Vienna, 1926) but he did not continue his studies to cover sand-mixtures, as he believed that sorting was bound to occur. Whether or not this is inevitable in some cases is still undecided. In bends and within the individual sandbanks it undoubtedly occurs, but there seems to be a redistribution which tends to keep constant the distribution of the total sand-discharge passing through any cross-section of the channel.

The problem yet to be solved is to relate the constants A, B, and C to the sand-mixture so they may be determined directly from a mechanical analysis. Kramer has found an empirical equation for C. Expressed in terms of the initial depth t_o instead of q_o, it is

$$C = st_o = 100/6 - d_g(\gamma_1 - \gamma)/M$$

where d_g is the mean grain-size. M is a sand-modulus found by dividing the arithmetical sand-analysis curve along the 50 per cent abscissa. The area below the line divided by the area above is M. It is essential to introduce into the equation some factor in addition to the mean grain-size which represents the distribution-curve of the sand. Thus the modulus M is a measure of the deviation of the curve from the vertical and so represents the volume of voids of the mixture. The constant C is the most easily determined, as it may be found by extending the plot of the bed-load against tractive power sq to the zero bed-load point. This method is superior to that employed by Kramer who located the point by a visual observation which is naturally subject to a personal error.

The constants A and B are interrelated and also dependent upon d_g and M or upon some expression similar to M. In sands so far analyzed they range from 100 to 1,000 and from 0.25 to 1.0, respectively. To find the relation between these constants and the sand-factors is the first objective of the laboratory research on bed-sediment. I believe they can be found by collecting and assimilating sufficient data. The relations will be empirical, but they must remain so until hydrodynamics is capable of solving the extremely complex problems of bed-sediment transportation.

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PROBLEMS IN DESIGN OF INLAND WATERWAYS TREATED BY MEANS OF HYDRAULIC MODELS

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The national government has authorized the United States Corps of Engineers to make extensive improvements in the navigation-channels of the Mississippi River System, and to develop new waterways where potential traffic is sufficient to justify the cost. The proposed project will provide navigation-channels with a minimum depth of nine feet in the main rivers; lesser depths, suitable to traffic conditions, will be provided in the principal tributary streams. In the Upper Mississippi Valley Division, which comprises the watersheds of the Mississippi and its main branches above the mouth of the Ohio River, the approved plan contemplates obtaining the project depth principally by canalization involving the formation of successive pools by construction of several relatively low-head dams with locks.

In planning the new structures of this great project the United States Engineer Department has found that small-scale models are almost indispensable in solving difficult problems in hydraulic design and in foretelling the navigation-condition of the rivers when the locks and dams have been completed. During the past three and one-half years, therefore, the design of the inland waterways of the upper Mississippi River System has been closely associated with and to a large extent based on findings in the study of hydraulic models. The experiments for this section of the rivers, directed by Colonel Wildurr Willing, District Engineer, St. Paul, Minnesota, have been conducted at the Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, by the writer.

The problems encountered in the design of navigation-structures which have been subjected to model-study may be divided into two general classes. In one group would be classified problems involving a general study of the hydraulic characteristics of a project to determine such factors as the following:

(1) Current-conditions upstream and downstream from the structure, especially in so far as the currents affect passage of traffic to and from the locks.
(2) The stability of the channel in the vicinity of the structure under the new flow-conditions created by the structure.
(3) The backwater-effect of the locks and dams on flood stages.
(4) The effect of spillway-discharge on the foundation of the structure and on the shorelines of the streams.

In this class the following projects have been studied or are in the process of being investigated at this laboratory:

(1) Lock and dam No. 2, Mississippi River at Hastings, Minnesota.
(2) Lock and dam No. 15, Mississippi River at Rock Island, Illinois.
(3) Marmet lock and dam, Kanawha River at Marmet, West Virginia.
(4) Lock and dam No. 2 Kiskiminitas River at Vandergrift, Pennsylvania.
(5) Montgomery Island lock and dam, Ohio River at Dashields, Ohio.
(6) Lock and dam No. 4, Mississippi River at Alma, Wisconsin.
(7) Lock and dam No. 26, Mississippi River at Alton, Illinois.

A somewhat different type of problem presented for model-study is that which deals with special features of a general project. The design of hydraulic details of a navigation-structure is often more easily made on the basis of observations of its

behavior in a model than on the basis of a theoretical analysis. In this type of problem the specific portion of the project to be treated in the model can generally be separated from the project as a whole and studied on a larger scale than would otherwise be practicable, thus permitting of a greater degree of accuracy in the experimental results.

The following problems falling in a classification of this nature have been investigated by the use of models.

(1) The toe-protection provided in the original design for the spillway of the Hastings dam consisted of a stilling-basin for 20 per cent of the spillway-length, and rock-filled cribbing and rip-rap below the remainder of the dam. A model of a section of the spillway to a scale of 1 to 14, indicated that the protection would not be adequate and a stilling-basin for an additional 20 per cent of the spillway was provided.

(2) Proposed submergible roller-gates for the Rock Island Dam required concave sills which under some conditions of operation would be subject to silting. A model proved that debris deposited in the depression could be removed by a simple manipulation of the gate and that lowering of the roller-gate into the recess would not be hampered by sedimentation.

(3) A stilling-basin to protect the toe of the spillway in the Marmet Dam to be located on a soft sandstone foundation was designed on the basis of observations on a model built to a linear scale of 1 to 22.5.

(4) Model-studies were made on the Marmet Lock and Dam to determine the effect of discharge from a proposed power-development on the navigation-condition in the downstream entrance to the locks. It was found that a training-wall placed in the path of the tailrace-current and parallel to the axis of the river would be necessary to safeguard river-traffic entering or leaving the locks.

(5) Questions of flotation under certain conditions of operation of the Marmet and Rock Island roller-gates led to an investigation of the pressure-distributions on models of the roller-gates. The tests indicated that if provision be made for free circulation of water in the drum and escape of air when the gate is in a partially submerged position, tension on the lifting chains will always exist.

(6) A stilling-basin was developed for the gravity-type spillway of Dam No. 4, Monongahela River, to protect the foundation against erosion. In the same model a crest shape for low-head, concrete overflow dams was developed which as indicated by the tests would greatly decrease the backwater-effect of the dam and minimize the danger of pitting on the crest.

(7) Considerable difficulty is experienced in the operation of beartrap dams on the Ohio River because debris lodges under the gates and prevents their being completely lowered. A model was studied to aid in developing a flushing system to eliminate this difficulty.

(8) A model of a ship-lock, scale 1 to 15, is being tested to determine the causes of and practical methods for preventing surges in the chamber and in the conduit-system while filling and emptying for the lockage of river-traffic. The time of lockage is an important factor in the cost of river-transportation and it is also the purpose of these studies to find means for reducing the time required to fill and empty the lock without increasing disturbances in the chamber.

(9) The hydrostatic loading on a double-leaf vertical-lift gate was investigated in a model and under certain operating conditions was found to exceed the weight of the gate alone by about 300 per cent. The excessive hoisting-capacity required to operate this type of gate precludes its use in most Mississippi River navigation-dams.

(10) Current-conditions below the lock at Keokuk, Iowa, make navigation to and from the lock at certain stages of the river very difficult and hazardous. The situation was studied in a model and a solution believed to be effective was obtained by building a permeable wing-wall to deflect the disturbing currents away from the lock-

approach. The model also demonstrated that the tailrace-level at the power-house could be lowered and thus the head on the turbines increased by removal of portions of a cofferdam left in place along the edge of the tailrace when construction of the powerhouse was completed.

The reliability of conclusions drawn from model-experiments and the limitations in their use can only be demonstrated by comparison of corresponding phenomena observed in the model and in the prototype. The program of investigation includes a study of conditions in the full-scale project when completed to determine the exactness with which those conditions were simulated in the model. A very scant amount of field data for comparison with the observations made on models described in this paper has been obtained to date; therefore, no conclusions regarding the validity of the model-laws can be presented at this time.

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EQUILIBRIUM-CONDITIONS IN DEBRIS-LADEN STREAMS

W. W. Rubey

Introduction

The work of streams is highly important in several fields of geology. Streams remove rock-debris from the sites of weathering and transport it to flood-plains, lakes, and ocean, where it is deposited to form new rocks. And during this erosion, transportation, and deposition, streams carve out and build up land-forms, such as mountains, valleys, and plains. Because of these multifold results of stream-activity, geologists have long been interested in the processes of stream-work. Fifty-six years ago, Gilbert formulated the major principles of stream-work and land-sculpture in a paper (G. K. Gilbert, Report on the geology of the Henry Mountains, U. S. Geog. and Geol. Sur. of the Rocky Mountain Region, pp. 99-150, 1877) which still, from the geological viewpoint, stands as the classic of the subject. The essence of Gilbert's ideas is the concept of graded streams--the concept that, either by cutting down their beds or by building them up with sediment, streams tend always to make for themselves channels and slopes that, over a period of years, will transport exactly the load of sediment delivered into them from above.

To geologists, faced with the difficult problems of interpreting the work of past streams, the principles formulated by Gilbert have been of immense value. Nevertheless, many questions arise in geological studies that can not be answered adequately by deductions from these qualitative principles. Gilbert, perhaps more than other geologists, recognized this fact and carried out extensive laboratory investigations in an attempt to establish quantitative relations between the many variables involved in stream-equilibrium. In this attempt he was only in part successful, but he has left on record (G. K. Gilbert, The transportation of debris by running water, U. S. Geol. Sur. Prof. Paper 86, 1914) a mass of observational data on the loads of known grain-size transported by graded streams that is probably unsurpassed anywhere.

Other workers, of course, have also made important contributions to our knowledge of the geologic work of streams. Besides the geologists, many physicists and engineers have discovered and investigated fundamental relationships in stream-dynamics that should have a direct application in strictly geological studies. But, to the writer's knowledge, no general expression that involves all the essential geologic factors has thus far been proposed.

In an attempt several years ago [W. W. Rubey, Geology of the Hardin and Brussels quadrangles, Illinois, State Geol. Sur. Ill. Bull. (awaiting publication); The Illinois River, a problem in channel-equilibrium, J. Wash. Acad. Sci., v. 21, pp. 366-367 (abstract), 1931; Alluvial islands--their origin and effect upon stream regimen, J. Wash. Acad. Sci., v. 22, p. 468 (abstract), 1932] to express the quantitative effect of the various factors that influence the slope of graded streams, the writer stumbled upon a method of attack which gives some promise that it may eventually lead to a general expression of stream-equilibrium. It is far from that now; but some

reading of the literature and more testing against published data suggest that the theory should probably be offered for criticism in its present state.

Derivation of general equation

Briefly, the concept is that in any unit of time, the loss of potential energy of water and debris in flowing downhill, E, plus the original kinetic energy, K_1, = the energy consumed in friction, F, plus the energy consumed in supporting the debris, D, plus the subsequent kinetic energy, K_2.

Proceeding, then, to evaluate each of these terms:

The loss of potential energy of water and debris in flowing downhill, E, = the mass of water and debris × the acceleration due to gravity × the vertical distance of fall.

Let ρ_w, ρ_s, and ρ_f represent the respective densities of water, debris-particles, and total fluid; v_w, v_s, and v_f, their mean velocities of flow or transportation (measured in cm/sec), and A_w, A_s, and $A_f = (A_w + A_s)$ their areas of cross-section in a channel (measured in cm^2), then

$W = \rho_w A_w v_w$ = mass of water passing a cross-section per unit time (in gms/sec)

$L = \rho_s A_s v_s$ = mass of debris passing a cross-section per unit time (in gms/sec)

$Q = A_f v_f$ = volume of fluid passing a cross-section per unit time (in cm^2/sec)

$\rho_f Q = \rho_f A_f v_f = \rho_f (A_w + A_s) v_f$ = mass of fluid passing a cross-section per unit time (in gm/sec)

But in a given length of channel, ℓ, corresponding, say, to the distance traveled by the water in t seconds

$$\text{mass of water} = \rho_w A_w \ell = \rho_w A_w v_w t = Wt$$

$$\text{mass of debris} = \rho_s A_s \ell = \rho_s A_s (v_s/v_s) v_w t = L\, v_w/v \cdot t$$

$$\text{mass of fluid} = Wt + L\, v_w/v_s \cdot t = \rho_f Q t \qquad (1a)$$

And in this mass of fluid

$U = 100\,(L\, v_w/v_s \cdot t)/(Wt + L\, v_w/v_s \cdot t)$ = concentration of debris in fluid (measured as percentage by weight)

so that

$$\text{mass of fluid} = 100\, W/(100 - U) \cdot t = \rho_f Q t \qquad (1b)$$

If v_w, the mean velocity of flow of the water, and v_s, the mean velocity of the transportation of the debris, were known to be the same (as they are commonly assumed to be), some of these definitions and symbols might have been omitted. But they have purposely been retained in order to show the difference between the quantity, L, usually determined in laboratory studies, and the quantity, U, measured in natural streams. The question raised here—the relative velocity of water and debris-particles—is of considerable importance in various engineering and geological problems; yet very little appears to be known about it. The larger particles transported have been observed (G. A. Daubrée, Géologie expérimentale, v. 1, pp. 250-251, 1879; Gilbert, op. cit., pp. 26-29, 1914) to travel more slowly than the finer material (partly, perhaps, because they move in lower filaments of the stream and partly because, with their larger mass and shorter leaps, they are not fully accelerated to the velocity of the fluid); but until we have experimental studies especially directed at this question, or a more adequate understanding of the precise mechanisms of the different modes of transportation so that these relative velocities can be calculated, we must make the customary assumption that

$v_w = v_s = v_f = v_m$ = mean velocity of flow of water, debris, and total fluid

Fig. 1--Method of evaluating the vertical distance that a mass of water and debris falls in flowing downhill

Then

$$\rho_f Q t = (W + L)\, t, \text{ which is an assumption} \quad (1c)$$

(2) The vertical distance that this mass of water and debris falls in flowing downhill (Fig. 1) is measured by the expression

$$e = hs = \ell \cos \alpha\, s \quad (2a)$$

For most natural streams, h is nearly equal to ℓ. When the angle α is 2°5 (a slope of 4.5 per cent or 235 feet per mile), $h = 0.999\ell$; when α is 8° (a 14 per cent slope), h is only one per cent less than ℓ; and even wher α is 18° (a 32.5 per cent slope or 1700 feet per mile), h is only five per cent less than ℓ. Inasmuch as the fluctuating discharge of natural streams makes the attainment of perfect equilibrium rare, and as even the laboratory data on stream-transportation is rarely so complete that it can be considered accurate to the nearest five or perhaps even ten per cent, it follows that in most natural streams the error is negligible if h is taken as equal to ℓ.

Now $v_m = \ell/t$ = mean velocity of flow along the length ℓ; therefore

$$e = v_m \cos \alpha\, st = v_m\, st, \text{ closely} \quad (2b)$$

(3) Summarizing these separate elements, the loss of potential energy of water and debris in flowing downhill,

$$E = (W + L) g v_m\, st^2, \text{ closely (measured in ergs)} \quad (3)$$

where g = acceleration due to gravity.

(4) The kinetic energy of the fluid, K = 1/2 mass × (velocity)^2. Thus

$$K_1 = 1/2\ (W_1 + L_1)\ t\ v_{m1}^2 = \text{original kinetic energy} \quad (4a)$$

$$K_2 = 1/2\ (W_2 + L_2)\ t\ v_{m2}^2 = \text{subsequent kinetic energy} \quad (4b)$$

Changes in the total kinetic energy along the course of a stream due to the addition of water and debris by large and small tributaries are likely to be relatively quite small, for the reason that each increment of added fluid brings with it its own quota of kinetic energy. And for relatively short portions of a stream, any changes of water-volume due to direct precipitation or evaporation or to ground-water discharge or loss will generally be negligible. Furthermore, on the average, there is no net increase nor decrease of the load by erosion or deposition in any graded portion of a stream; that is, the load carried out past the lower end of a graded portion will, over a period of years, equal the load delivered at the upper end. To these considerations about changes of kinetic energy from point to point along the course of a stream may be added the statement that at some mean flood-stage (which corresponds closely to the bank-full stage) a stream does its most effective work upon its channel; and it is to the condition of flow at this particular stage that a stream tends to adjust its channel. Consequently, between adjacent sections of a graded stream, the conditions are essentially those of uniform flow and the changes in kinetic energy are, on the average, negligible. That is,

$$1/2\ (W_1 + L_1)\ t\ v_{m1}^2 = 1/2\ (W_2 + L_2)\ t\ v_{m2}^2, \text{ closely} \quad (4c)$$

(5) The energy consumed in friction, F = area of channel-surface × force per unit-area × distance through which the total force acts. (Additional friction-losses due to

bends in the channel and to changes of cross-section area are neglected here because they seem clearly to be of second-order magnitude).

The area of channel surface = the total wetted perimeter of channel cross-section, P, x the length of channel, $\mathcal{L}$ (5)

(6) The force per unit-area, f, which resists fluid-flow, has been investigated carefully by many workers. For laminar (viscous) flow, this force varies as the first power of v_m but above a certain critical velocity (or more strictly above a certain Reynold's number), which is exceeded in practically all natural streams, the flow is turbulent; and in turbulent-flow, f has been found to vary as some power of v_m between 1.65 and 2.0 (usually between 1.9 and 2.0 in natural streams). If we put

$$f = k \rho_f v_m^2 \tag{6a}$$

then, k, the coefficient of friction of the fluid, will be one that varies somewhat. One empirical expression (C. H. Lees, On the flow of viscous fluids through smooth circular pipes, Proc. R. Soc. London, v. 91, A, pp. 46-53, 1915; T. E. Stanton, Friction, pp. 55-56, London, 1923; H. L. Dryden, F. D. Murnaghan, and H. Bateman, Report of the Committee on Hydrodynamics, Nat. Res. Council Bull. No. 84, p. 337, 1932) of this variation, founded upon a great many observations of the resistance to the flow of water, oil, and air through smooth pipes of different sizes, is

$$k = 0.0047 \left[\mu/(\rho_f v_m r)\right]^{0.35} + 0.0009 \tag{6b}$$

where μ = the coefficient of viscosity of the fluid, r = A/P = (area of channel cross-section)/(wetted perimeter) = 1/4 diameter of circular pipe = hydraulic radius of channel, which in wide, relatively shallow streams is essentially equal to the mean depth. Conceivably the variation of k might be quite different for flow in natural stream-channels.

(7) The total force, $P\mathcal{L}f$, acts through the distance, $\mathcal{L}$, therefore

$$F = P\mathcal{L}f\mathcal{L} = P v_m t \left(k \rho_f v_m^2\right) v_m t = k \rho_f P v_m^4 t^2 \text{ (measured in ergs)} \tag{7}$$

(Dimensionally, this quantity, total force times distance, like all others in the general equation, is ML^2/T^2.)

(8) The energy consumed in supporting debris, D, = the effective mass (in fluid) of debris x the acceleration due to gravity x the distance through which the debris would fall if unsupported.

From the definitions of densities and weights given under Section (1) above and from equation (1c)

$$\rho_f = (W + L)/(W/\rho_w + L/\rho_s) = \text{average density of muddy fluid} \tag{8a}$$

then

$$\text{effective mass of debris} = (L - \rho_f L/\rho_s)t = L(\rho_s - \rho_f)/\rho_s \cdot t$$

$$= \frac{LW}{\rho_w} \cdot \frac{\rho_s - \rho_w}{(\rho_s W/\rho_w) + L} \cdot t \tag{8b}$$

But this effective density of the debris can be estimated with sufficient accuracy from the much simpler equation,

$$\text{effective mass of debris} = L(\rho_s - 1)/\rho_s \cdot t \tag{8c}$$

Even such notoriously muddy streams as the Missouri River commonly carry but 1/10 to 2/10 of one per cent of solid matter (R. B. Dole and H. Stabler, Denudation, U. S. Geol. Sur. Water-Supply Paper 234, p. 89, 1909). Exceptionally, however, certain rivers like the Colorado transport upwards of 10 per cent by weight of solids (C. S. Howard, Suspended matter in the Colorado River in 1925-1928, U. S. Geol. Sur. Water-Supply Paper 636, p. 32, 1929), and during "flash-floods" a few small streams in arid regions are known to carry from 40 to 60 per cent by weight (C. S. Howard, personal communication)

of solid matter. Taking $\rho_s = 2.65$ and $\rho_w = 1.00$, then for heavily-laden streams that carry one per cent by weight of solids, the simpler equation (8c) gives a value for the effective mass of debris that is only 4/10 of 1 per cent too low; and even for such exceptionally heavy loads of debris as 10 per cent, this simpler equation is but 4 per cent too low.

(9) The distance through which the debris would fall if unsupported is here assumed to be equal to the time of flow multiplied by the mean settling-velocity of all particles that are moved when off the bottom of the stream (that is, all particles transported by suspension or saltation). This assumption, of course, neglects the true bed-load (the portion of the load that, strictly speaking, simply rolls or slides along the stream-bed), and for that reason it is not completely satisfactory. Nevertheless, the debris that travels entirely by rolling or sliding along the bottom must move at a velocity so much less than that of the leaping and suspended material (see Gilbert, op. cit., p. 27, 1914) that, considering both quantities per second and velocities, it is probably of negligible proportions in most natural streams. Furthermore, it is worth noting in this connection that the term "bed-load," as commonly used, includes all debris on and near the stream-bed (that is, not only the rolling, sliding material, but also the quantitatively more important portion that travels by saltation).

The settling-velocities with which different particles fall through a fluid depend chiefly upon the density and volume of the particles and the density and viscosity of the fluid. It is true that other factors, especially differences of shape (W. W. Rubey, Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region, U. S. Geol. Sur. Prof. Paper 165, pp. 17-18, 23-24, 26-27, 1930), also influence settling-velocities; but, for all except the flat micaceous plates, these other factors seem to be relatively unimportant. For small particles, the resistance of the fluid depends largely upon its viscosity, and these small particles fall with velocities that are given closely by Stokes' law

$$v_{v1} = g/18 \cdot (\rho_s - \rho_f)/\mu \cdot d^2 = \text{vertical velocity or settling-velocity of small particles (measured in cm/sec)} \qquad (9a)$$

where d = diameter of particle (measured in cm). But for large particles the resistance appears to be controlled by the impact of the fluid, so that

$$v_{v2} = [2/3 \cdot g(\rho_s - \rho_f)/\rho_f \cdot d]^{1/2} = \text{settling-velocity of large particles} \qquad (9b)$$

Particles of intermediate sizes fall with velocities that appear to vary as powers of the diameter intermediate between the square and the square-root (R. H. Richards, Velocity of galena and quartz falling in water, Trans. A. I. M. E., v. 38, pp. 210-235, 1908). For the settling-velocities of both large and small particles, the writer has proposed elsewhere (W. W. Rubey, Settling-velocities of gravel, sand, and silt-particles, Amer. J. Sci., v. 25, pp. 331-338, 1933) the general formula

$$v_{v3} = \frac{[2/3 \cdot g\, \rho_f(\rho_s - \rho_f)d^3 + 36\mu^2]^{1/2} - 6\mu}{\rho_f d} \qquad (9c)$$

which seems to accord closely with published data.

(10) Summarizing the separate elements, the energy consumed in supporting debris

$$D = L\,(\rho_s - 1)/\rho_s \cdot g\, v_{v3}\, t^2, \text{ closely (measured in ergs)} \qquad (10)$$

(11) The general energy-equation of stream-work, $E + K_1 = F + D + K_2$, may now be written by assembling these separate evaluations and approximations of the different terms

$$(W + L)\, g v_m s t^2 = k\, \rho_f\, P\, v_m^4\, t^2 + L\,(\rho_s - 1)/\rho_s \cdot g v_{v3} t^2, \text{ approximately} \qquad (11a)$$

and, dividing by t^2, this becomes

$$(W + L)\, g v_m s = k\, \rho_f\, P\, v_m^4 + L\,(\rho_s - 1)/\rho_s \cdot g v_{v3} \qquad (11b)$$

Tests and possible applications of equation

So many approximations and rather doubtful assumptions have gone into the derivation of equation (11b) that it is essential to test it against other general formulae and empirical data.

First, it is of interest to note that when L = 0

$$(W + L)\, g v_m s = \rho_f Q g v_m s = \rho_f A_f g v_m^2 s = k \rho_f P v_m^4$$

and

$$v_m = [g/k \cdot A_f/P \cdot s]^{1/2} = [g/k \cdot rs]^{1/2}$$

This equation is the familiar Chezy formula with the usual coefficient C here represented by $(g/k)^{1/2}$. Values of the coefficient C may be estimated from numerous engineering formulae (Mansfield Merriman, Treatise on hydraulics, 10th ed., pp. 272-317, 1930). For natural stream-channels, this coefficient (computed in terms of centimeters instead of feet, as is customary) commonly ranges from about 300 to 800. If g is taken as 980, a value of C = 350 corresponds to k = 0.008 and a value of C = 700 corresponds to k = 0.002.

The data required to test adequately equation (11b) are difficult to find in the literature; very rarely do all the significant quantities appear to have been determined simultaneously. Gilbert's hundreds of individual experiments (Gilbert, op. cit., pp. 38-54, 69-70, 1914) on the quantities of sand and gravel transported under conditions of essential equilibrium in small laboratory streams perhaps fill these requirements as nearly as they have thus far been met. With these data the equation may be tested by calculating values of the single empirical constant, k, and comparing these values with those found in other types of investigations.

By changing Gilbert's data from feet to centimeters, calculating the mean velocity from the discharge, load-volume, and channel-dimensions, estimating the wetted perimeter as (width + twice mean depth), and assuming that the load was transported almost entirely by suspension and saltation and that the energy spent in transportation is measured by the mean settling-velocity given by formula (9c), it then becomes possible to derive values of the coefficient of friction, k, in equation (11b). From among the large group of these experiments in which some debris was transported, 22 individual experiments were selected to represent the extreme conditions of experimentation. In this group, the volume of water discharged ranged from 0.093 to 1.119 ft^3/sec, the mean velocity of flow ranged from 1.0 to 5.1 ft/sec, the width of channel ranged from 0.66 to 1.96 feet, the slope of the stream-bed ranged from 0.0016 to 0.0226, the particles carried ranged from 0.3 to 7.0 mm in diameter, and their concentration in the fluid ranged from 0.013 to 1.83 per cent by weight. For this group, the calculated values of k ranged between extreme limits of 0.003 and 0.009 with a median value of 0.0046 and a semi-quartile range of 0.001. For another group of 20 of Gilbert's experiments in which no debris was transported, the velocities were considerably lower and the calculated values of k had a median value of 0.007 and a semi-quartile range of 0.003.

These 42 values seem to show that the coefficient, k, varies inversely as some function of vr, as might be expected from the resistance to flow through pipes as given in equation (6b), but the values are from 2 to 5 times as great as those given by this equation, with the discrepancy increasing as the materials making up the stream-bed become larger. This discrepancy might possibly arise from the estimation of the wetted perimeter as simply (width + twice mean depth), for this formula neglects all irregularities of the channel-surface caused by pebbles and the larger sand-grains. If, because of these irregularities, the values of P should properly, let us say, be doubled, then the calculated values of k would be reduced by one-half.

Data on natural streams, comparable to that on Gilbert's laboratory models, are difficult to obtain. However, the writer's colleague, C. S. Howard, has kindly furnished unpublished data on the Colorado River near Grand Canyon, Arizona, which afford a basis for estimating the value of the coefficient, k, in large, heavily-loaded, natural streams. From measurements of the percentage-concentration of suspended material in the River, from partial mechanical analyses which indicate the percentage of different sizes in this suspended material, from stage-readings at the time of sampling,

from records of velocity-measurements and channel-sizes at comparable river-stages, and from a published profile of the River, it is possible to calculate estimated values of k. In this calculation, the wetted perimeter was assumed to be given by the formula (width + twice mean depth), an assumption that gives too small a value of P, and thus too large a value of k, because it neglects not only the minute irregularities of channel-surface around sand-grains and boulders but also the larger irregularities in the channel which would be indicated by closely-spaced soundings. Estimated by this method, k was found to be about 0.006 on June 8, 1928, when the discharge was about 80,000 ft^3/sec, the mean velocity 9.0 ft/sec, and the suspended matter 0.86 per cent by weight; on June 27, 1928, when the discharge was about 39,000 ft^3/sec, the mean velocity 6.0 ft/sec, and the suspended matter 0.38 per cent, k was about 0.010; and on July 31, 1929, when the discharge was about 52,000 ft^3/sec, the mean velocity 7.2 ft/sec, and the suspended matter 8.03 per cent, k was about 0.007.

These estimates of the value of k on the Colorado River are not to be taken too seriously; but they do seem to indicate that in large heavily-laden streams k is of about the same order of magnitude that it is in small laboratory streams. To calculate the values more accurately, complete mechanical analyses of the suspended material would be essential; and also far more exact data on the discharge, mean velocity, and wetted perimeter of the River would be needed.

Certain corollaries may be derived from equation (11b) which are of interest because they afford bases for tests of an entirely different sort. If we assume that the Chezy formula, $v_m^2 = C^2 rs$, is approximately correct and substitute $C^2 rs$ for v_m^2 in equation (11b), we get

$$\frac{(\rho_s - 1)/\rho_s \cdot L\, v_{v3}}{(W + L)\, v_m s} = 1 - k\, C^2/g \qquad (13)$$

And if k varies inversely as C^2 [as has been suggested by the derivation of the Chezy formula given in equation (12)], the proportion of the total stream-energy spent in supporting debris will be approximately constant. In the 22 experiments by Gilbert on debris-laden streams recalculated by the writer, the values of $(1 = k\, C^2/g)$ range range from 0.007 to 0.047 with a median value of 0.025 and a semi-quartile range of 0.007. That is to say, under the conditions of these experiments, 97.5 per cent, on the average, of the total stream-energy appears to have been lost in friction and only 2.5 per cent spent in transporting debris. The data for the Colorado River indicate values of $(1 - k\, C^2/g)$ of 0.039, 0.022, and 0.152, respectively, for the three days mentioned above. Rough computations, based upon fragmentary data, suggest values of from 0.03 to 0.08 for portions of the upper Mississippi, the Missouri, and the Illinois rivers.

Obviously, however, the proportion of total stream-energy spent in transportation can not remain even approximately constant under all conditions of stream-flow; because when (as in a number of Gilbert's experiments) a stream is unable to get debris that is small enough for it to transport, the energy spent in transportation is zero and k/g is equal to C^2. Whether or not any of the stream's energy is spent in transportation manifestly depends upon a factor that was not considered in the derivation of equation (11b). This neglected factor does not affect the total energy spent in both friction and transportation and so its neglect does not invalidate equation (11b); but it does control, or at least influence, the distribution of energy between these two forms of work.

The neglected term is one that would express the mutual relationships among (a) the fluid velocities very close to the stream-bed, (b) the largest particles that these "bed-velocities" will move, and (c) the size and quantity of the smallest particles that are available to the stream. This term might, perhaps, be called the "mobility" of the stream-bed. According to classical theory (for discussion and references see Gilbert, op. cit., pp. 16, 68, 162-163, 215-216, 1914; W. H. Bucher, On ripples and related sedimentary surface-forms and their paleogeographic interpretation, Amer. J. Sci., v. 47, pp. 150-151, 1919), debris particles remain motionless on a stream-bed until the passing fluid attains a certain velocity; and this competent velocity, as it has been called, increases as the square-root of the particle-diameters (the "roughness" and slope of the stream-bed remaining constant). Yet, it is important to note that this velocity required to move grains of a certain size is not

the mean velocity of the entire stream but that of the fluid filaments very close to the stream-bed; and it is notoriously difficult either to measure or to calculate the velocities near a stream-bed. According to an alternative theory (Richard Winkel, The limits of transferability of experimental results, and model-similarity in river hydraulic experiments, Hydraulic Laboratory Practice, pp. 57-58, 1929; Francesco Marsolo, Some considerations regarding hydraulic models, idem, p. 755), the motion of a particle depends not upon velocity of flow but upon the component of fluid weight in the direction of stream-flow; and thus the "critical transporting-force," measured as depth × slope, varies closely as the particle-diameters. Other theories of the critical forces required to move particles might also be mentioned, such as that depending upon the rate of shear between adjacent fluid filaments (Harold Jeffreys, On the transport of sediment by streams, Proc. Cambridge Phil. Soc., v. 25, pp. 272-276, 1929), but enough has already been given to show that no general agreement has yet been reached on this important question.

But, whatever may be the precise relations near the limiting condition (in which the smallest particles available to a stream can not be moved by the existing forces), the suggestion still remains in the data cited that, once this limit of competence is passed, the energy spent in transportation tends to be roughly the same proportion--only a few per cent--of the total energy of the stream. Furthermore, it seems likely that in natural streams flowing in alluvial channels (that is, in channels composed of materials laid down at other stages of the same streams) this factor of competence plays no very important part, for the reason that these streams can almost always find adequate supplies of material fine enough for them to transport.

Another substitution of the Chezy formula into equation (13) gives a rather interesting expression of this energy spent in transportation, per unit mass of fluid, namely

$$\frac{(\rho_s - 1)/\rho_s}{C\,(1 - k\,C^2/g)} \cdot \frac{L\,v_{v3}}{\rho_f Q} = s^{3/2}\,r^{1/2} \qquad (14)$$

This equation may also be interpreted as showing the mutual adjustments of slope and hydraulic radius which are necessary in order that a stream may accommodate itself to a given load, grain-size, and discharge. With the exception of the term for the hydraulic radius, this equation states general relationships that have long been familiar to geologists, namely, that the graded slope varies directly as the amount of debris that must be carried, directly as the average size of this material, and inversely as the volume or mass of water discharged by the stream.

The mutual relationships of depth and slope suggested by equation (14) may be examined more readily if the depth term is put into a somewhat different form. Let X = mean depth / width = the "form-ratio" or proportionate depth of a channel = r / P, approximately, in wide relatively shallow streams. Then

$$r = A/P = Q/(C\sqrt{rs}\,P) = QX/C\,r^{3/2}\,s^{1/2})$$

and

$$r^{1/2} = Q^{1/5}\,X^{1/5}/(C^{1/5}\,s^{1/10})$$

Substituting this value of $r^{1/2}$ in equation (14) gives

$$s^{7/5}\,X^{1/5} = \frac{(\rho_s - 1)/\rho_s}{C^{4/5}(1 - kC^2/g)\rho_f} \cdot \frac{L\,v_{v3}}{Q^{6/5}} \qquad (15)$$

If $C^{4/5}(1 - kC^2/g)\rho_f$ remains approximately constant, this equation is in a form suitable for comparison with certain observational data.

The competence terms in Gilbert's general empirical equation (Gilbert, op. cit., p. 191, 1914) vanish for large (op. cit., pp. 66-67, 153) and either very wide (op. cit., pp. 125,129-130) or essentially adjusted (op. cit., pp. 129-130) streams [this generalization of Gilbert's empirical equation for large streams is discussed more fully in Rubey, op. cit., Ill. Geol. Sur. Bull. (awaiting publication)] so that

$$L \propto s^{a1}\,Q^{a2}\,d^{a3}\,X^{a4}$$

where a1, a2, a3, and a4 are empirical exponents. The values of these exponents, determined by Gilbert (Gilbert, op. cit., pp. 187, 132-134) from data on laboratory models, are: a1, from 0.93 to 2.37 with a mean value of 1.59; a2, from 0.81 to 1.24 with a mean value of 1.02; a3, from 0.50 to 0.62 with a mean value of 0.58; and a4, from 0.06 to 1.55 with a mean value of 0.47.

From detailed published measurements of the channel-dimensions of certain portions of Illinois River that are believed to be in almost perfect equilibrium, the writer obtained [Ill. Geol. Sur. Bull., op. cit. (awaiting publication), and J. Wash. Acad. Sci., op. cit., v. 22, p. 458, 1932) the expression

$$s \propto x^{1/6} a\, L^{2/3}/Q^{5/6}, \text{ approximately}$$

Equation (15) gives no direct value of the exponent of the particle-diameters, d, but from a plot of equation (9a) it was found that, for the sizes used by Gilbert, the slopes of the curve correspond to exponents of from 0.5 to nearly 0.9 with a mean for all of the sizes of approximately 0.65.

These different determinations of the various exponents may be tabulated for more convenient comparison as in Table 1.

Table 1

Values	Values of exponents of				
	s	X	L	d	Q
Theoretical from equation (15)	1.40	0.20	1.00	0.65+	1.20
Mean in Gilbert's empirical equation	1.59	0.47	1.00	0.58	1.02
Calculated from a portion of Illinois River	1.50	0.25	1.00	?	1.25

The inverse relation between slope and proportionate depth indicated in equation (15) seems to be confirmed qualitatively by published measurements (A. A. Humphreys and H. L. Abbott, Report upon the physics and hydraulics of the Mississippi River, U. S. Corps Engineers Prof. Paper No. 13, pp. 107, 122, 1861, reprinted 1876; U. S. Engineer Corps, Survey of Mississippi River from St. Louis, Missouri, to its mouth, U. S. House of Representatives, 61st Cong., 1st sess., Doc. No. 80, pp. 11, 34, 76-77, 1909) on large navigable streams. These measurements indicate that, other things being approximately equal, the deeper narrower portions of a stream tend to have flatter slopes; and artificial deepening of a channel appears to flatten the slope after a number of years. Additional evidence bearing on this inverse relation between slope and proportionate depth has been discussed more fully by the writer elsewhere (Ill. Geol. Survey Bull., op. cit., awaiting publication).

The general validity of equation (15) may also be tested qualitatively by comparison with the normal behavior of natural streams. From head to mouth down most streams, the load, grain-size, and discharge gradually change. Because of the confluence of tributaries, the discharge usually increases greatly down a stream. Because of decreasing side slopes along the stream-course, the load added per unit-volume of water tends to decrease downstream. And because of mutual abrasion and attrition, the particles transported tend to become finer grained downstream. Hence, according to equation (15), the slope should usually flatten downstream. As is well known, the concavity of longitudinal stream-profiles, which results from this progressive flattening of the slopes downstream, is so common as to be almost universal (Henry Gannett, Profiles of rivers in the United States, U. S. Geol. Sur. Water-Supply and Irr. Paper 44, 1901).

Other more strictly geological tests of the validity of the general equations might also be made, but they would be somewhat out of place in the present paper. However, it is hoped that readers who have access to data of any sort which bear on the equilibrium-conditions in debris-laden streams will use them as a basis for criticism of the general equations that have been proposed here.

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DIVERSION OF SEDIMENT AT BRANCHING CHANNELS

Gerard H. Matthes

1--The object of this paper is to stimulate interest in research relating to the division of the bed-load at stream-forks. This much-neglected chapter in dynamics of streams has lately become of intense practical interest to hydraulic engineers as well as to scientists. Comparatively few of its many phases have been investigated to any extent.

2--One well-known phase, which has received much attention, is concerned with preventing sediment, more especially the heavier bed-load materials, from entering the intakes of irrigation-canals. This problem has intrigued man's ingenuity as far back as history is written, yet, today, its solution is far from perfect and some of its aspects are but little understood.

3--Some progress has been made, notably in Europe, in devising methods for preventing sedimentation at intakes of water power-plants. Of historic interest in this particular are the experiments performed by H. Thoma, H. Bulle, and Theo. Rehbock, in connection with a sedimentation-problem at a power-plant on the Middle Isar River. These experiments showed that a flume, rectangular in cross-section, diverting 50 per cent of the flow from another flume of identical cross-section, could be made to relieve the latter of as much as 97.3 per cent of its bed-load. The ratios of bed-load diverted for different bifurcation-angles were found to be as follows:

Angle at bifurcation	Ratio of water diverted, per cent	Ratio of bed-load diverted, per cent
30°	50	97.3
60°	50	96.2
90°	50	90.5
120°	50	87.5
150°	50	92.0

Summarized, these experiments demonstrated that a branch-channel, other things remaining equal, diverts most of the bed-load. Dr. Rehbock (Wasserbaulaboratorien Europas, 1926, p. 164; see also translation by John R. Freeman in Hydraulic laboratory practice, 1929, p. 179), commenting on the results obtained, states that it was not found possible, by any method, to cause the greater proportion of the bed-load to go down the straight channel.

4--Similar experiments made at the United States Waterways Experiment Station of the Mississippi River Commission, with flumes of various types, do not confirm the high ratios above quoted, but indicate that the branch-channel carries, in proportion to its discharge-capacity, more bed-load than the straight channel does below the point of diversion. These experiments have further demonstrated the importance of continuing the duration of any experimental run until a stabilized condition is reached in the branch-channel as regards both flow and bed-load movement. Failure to obtain such stabilized condition leaves the experiment inconclusive as regards the branch-channel being either a continuous diverter of bed-load materials or merely a storage-place for such materials, with the added possibility that its storage-capacity may be quite limited. Definite determination as to its true function in these respects is of paramount importance in applying this principle of bed-load diversion to actual river-conditions.

5--To illustrate, assume a channel-bifurcation at the head of a large island and that it is desired to divert as much bed-load material as possible into the secondary channel with a view to causing it to fill and cease to be a channel. It becomes of utmost importance to learn through laboratory experiment what portion of the bed-load diverted, under any given set of conditions, is likely to be permanently deposited in the secondary channel, and conversely what portion is likely to continue to travel down this channel and eventually reenter the main channel at the foot of the island. In one of the flume experiments made at the United States Waterways Experiment Station, it required 70 hours of continuous operation to bring about a condition of equilibrium. During the first 14 hours the bulk of the bed-load materials entering the branch-channel dropped and built up bars. This was followed by a period of bed-

load travel in which dunes and loose materials alternately predominated, followed by a condition of equilibrium in which dunes and loose materials progressed with regularity. The stabilized condition showed the branch-channel to discharge about 37 per cent of the total flow, and about 66 per cent of the total bed-load. It was found, furthermore, that the bed-load movement, although consisting of these two distinct forms, always totaled the same. In this instance the branch-channel did not fill with sand, but maintained its discharge-capacity while at the same time carrying more sand in proportion to its discharge than the main river-channel.

6--It seems strange that the hydraulic principle here discussed should have received such scant recognition in the past, considering the vast possibilities which it opens up in its practical application. The reason for this appears to be twofold: (a) Field observations on bed-load movement in rivers are notoriously difficult to make; (b) laboratory experiments, to date, are only just beginning to reveal the important rôle played by the bed-load. Recently, the desirability of being able to control the division of the bed-load at river-forks has been recognized by engineers of the Mississippi River Commission as being of major importance in the stabilization of a river-channel having unstable beds and banks. Nature's way of dividing the bed-load at bifurcations has been found to be a most important, if not the controlling, factor in the proportioning of the channels below any bifurcation. And this is reflected in the many troublesome problems that arise in river channel-regulation wherever an island or a group of islands divide the flow, or again where an appreciable portion of the discharge is permanently abstracted from a stream. Such study as has been given to the subject indicates that it is practicable, by means of suitable engineering works, to modify nature's division of the bed-load and thus affect to a marked degree the local morphology of a stream. This aspect of the subject has profound economic significance.

7--It is scarcely necessary to point out that the early experiments above referred to, made as they were in rectangular flumes, are not representative of natural channel-conditions. In the operation of the latter a number of variable factors enter which demand recognition. The more important of these are: (a) The location of the point of diversion with respect to the curvature of the main channel; (b) the shape of the bifurcation, more especially that of the entrance to the branch-channel; (c) the shape of the channel cross-sections; (d) the ratio in which the flow is divided; (e) variations in total inflow or in stage; (f) water surface-slopes; and (g) the mechanical composition of the bed-load. These seven variables set up a large number of combinations. As exhibited in nature these combinations cause endless variation. Research work, to be conclusive, must take account of all these variables and perhaps others of local importance peculiar to a given project. Assuming a series of experiments to be undertaken on a model of a given river-bifurcation, then various combinations of variables (b) to (g) inclusive will be required, while (a) remains the same throughout. The nature of the problem may render it possible to eliminate many of these combinations, thus reducing the laboratory work to some extent. Nevertheless, it will be obvious that any experimental series in this field of research will necessarily be lengthy.

8--The following tabulation will assist in visualizing the wide scope which this field of research offers. The list, admittedly is incomplete, but it is felt that a more detailed treatment would not be commensurate with the scope of this paper.

Group A--Division of bed-load at a channel-fork, with subsequent return of the diverted flow into the main channel

(a) At an island
(b) At a group of islands
(c) At a slough or an abandoned channel which becomes active during high stages
(d) At the intake of a water power-plant

Group B--Diversion of bed-load into branch-channels which permanently abstract a portion of the river-discharge

(a) Natural outlet channels, as for instance those of a delta-building stream
(b) Artificial diversions such as irrigation-canals
(c) Floodways and flood-relief spillways, either controlled or uncontrolled
(d) Accidental discharge during high stages, as through levee-breaks

Group C--Movement of bed-load in channels subject to reversible flow, tidal and non-tidal

(a) Tributaries of a tidal river or estuary
(b) Mouths of tidal basins, inlets, and flats
(c) Non-tidal tributaries subject to backwater from the parent stream, especially those having large areas of low lands inundated by backwater
(d) Outlet channels (so-called inlets) connecting sounds with the ocean

10--In addition to the subdivisions set forth in the foregoing tabulation, it becomes necessary to recognize another subdivision. This relates to the two classes--A and B--of sediment-bearing streams which exist, each of which calls for separate treatment; that is, their characteristics differ so widely that the experimental findings applying to one will not, ordinarily, be found to be applicable to the other.

Class A--Those having flat, or nearly flat, transverse profiles normally devoid of talweg depressions. Streams of this class may be aptly described as overburdened with sediment in the sense that they cannot, except at very high stages and usually for only short periods annually, transport their allotted sediment-burdens. They may be either aggrading or eroding streams. Many of the rivers of the arid West, notably the Colorado River and a number of Great Plains streams, belong in this category. During falling flood-stages their kinetic energy is so completely absorbed in moving sediments of both suspended and bed-load types, that they are unable to clear their talwegs and in consequence their beds, at ordinary and low stages, are level across, devoid of any talweg depressions.

Class B--Streams which have more or less concave beds with well-developed talwegs and cross-overs. Streams of this type, as a rule, are capable of transporting more sediment than they normally do. Except during low and falling flood-stages they have kinetic energy to spare for the movement of both suspended and tractional load. This excess energy is expended in accelerated velocity, in turbulence, and in eddies. The great majority of rivers in the eastern half of the United States, including the Mississippi River, belong in this class. As in the previous classification, both aggrading and eroding streams are included. An interesting sub-division are clear-water mountain streams which turn turbid only after rains or heavy snow melting. A peculiar characteristic of such clear-water streams is the coarseness of the debris which they transport. Because of this peculiarity they afford unusual opportunity for the study of their bed-load movement.

11--In the case of streams possessed of well-defined talwegs, the most important factor which affects the ratio of bed-load materials diverted by a branch-channel, is the location of the point of diversion with respect to the curvature of the main channel. This is because the bed-load follows a well-defined path of travel in streams of this type. This path which has been observed in laboratory models as well as in clear-water streams, may be roughly described as running from convex bend to convex bend, crossing the channel at the cross-overs, but never coinciding with the talweg. Water diverted from a river along a convex bank therefore is likely to entrain large volumes of heavy sand, while diversions made along a concave bank are likely to entrain no bed-load but only sediments in suspension. Experimentation with a model of a Mississippi River bend at the United States Waterways Experiment Station has demonstrated that a diversion of ten per cent of the river-discharge at a point along the lower end of a convex bank in a short-radius bend, may entrain as much as 80 per cent of the bed-load. By contrast, in the same model, a ten-per-cent flow-diversion along the lower portion of a concave bank caused no bed-load whatever to be entrained. In both experiments, the flow-diversions were made to simulate water leaving the river through levee-breaks. European engineers, for many years, have found the concave bank best suited for diversions for hydro-electric plants, such locations being especially free from sedimentation-troubles at intakes and forebays. This confirms the practical application of this aspect of bed-load diversion.

12--In the case of overburdened streams possessing no talwegs (Class-A type, paragraph 10), location of the diversion-entrance with respect to curvature of the main channel is not the controlling factor in bed-load diversion which it is in Class-B streams. This is because in Class-A streams the bed-load is distributed over the entire cross-section. As many of our western streams used for irrigation are of the Class-A type, the excluding of heavy sediments from canal-entrances presents, therefore, many difficulties. Merely locating a canal-headgate in a concave bank does not solve the problem.

13--Second in importance as affecting the ratio of bed-load diverted from Class-B streams, is the shape of the entrance to the diverting channel. Altering the entrance produces marked changes. Experimental work has shown that this affords much opportunity for profitable investigation. This is indication that frequently important changes in a river like the Mississippi are due to gradual changes in bifurcations caused by bank-caving and accretion. These may cause the main channel to become the principal diverter of bed-load materials, relieving the secondary channel to the extent of causing it to deepen and widen and eventually become the main channel. Instances of this kind are numerous in alluvial streams, and are customarily explained as having been caused by the shifting of the talweg from the main to the secondary channel--thus confusing cause and effect.

14--Among the many problems that are linked up with the diversion of bed-load materials at branching channels, and concerning which much remains to be learned, may be mentioned the following: The much-mooted question as to the effect of levee-breaks and the operation of fuse-plug levees in causing deposits in the rinver-channel below; the manner in which sand and silt are carried back and forth in tidal channels, with attendant bar-formation, and the methods required for curing such conditions, thus eliminating frequent dredging; the location of jetties at river-mouths with special reference to littoral currents and bar-building; increasing navigable depths in both tidal and non-tidal streams by diverting part of the bed-load into side channels.

15--The subject here presented should be of singular interest to those in charge of hydraulic laboratories for the reason that the laboratory at present is the sole agency that can reliably determine the nature of bed-load movement. Engineers charged with river-regulation may, at times, be in position to ascertain through personal observation on streams the approximate ratio of bed-load division at a point of bifurcation. In general, however, they are helpless when it comes to determining actual bed-load quantities and the rates of their movement for different stages. Engineers must therefore rely on the laboratory for answers to such questions. Their questions will be many, judging from the fact that the present trend of thought is centered on the bed-load and methods of controlling its movement. The materials in suspension have become of secondary importance. Control of the bed-load is the key to the situation in a vast array of river-problems.

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MOVABLE BED-MODELS

Herbert D. Vogel

Hydraulic models for the solution of problems relating to the improvement of river and harbors may be grouped into two general classes distinguished from each other by the character of the bed employed. The purpose of this discussion is to present a brief but comprehensive outline of the methods of design and utilization of movable bed-models, but before this can be done it will be necessary to differentiate briefly between the two types, and to describe their particular fields of usefulness.

A fixed bed-model may be considered as any hydraulic model simulating in miniature a natural or artificial watercourse whose bed and banks are essentially non-erodible, so far as the problem at hand is concerned. Such models are particularly adapted to the precise determination of water-surface elevations, slopes, backwater, and sundry related factors and effects.

A movable bed-model, on the other hand, simulates the bed and banks of a natural stream or artificial channel which is subject to scour and erosion. The materials for the model must be so selected that when acted upon by the flow therein they will be scoured, deposited, or transported in suspension or by hydraulic traction, in a manner similar to that which is characteristic in nature. It can be seen that the use of models on this type greatly enlarges the field of problems which can be studied by laboratory methods.

When the United States Waterways Experiment Station is directed to undertake a model-study for any one of the various Engineer Districts of the United States, the

first step in the procedure is a general study of the problem and the acquisition of all pertinent data. These data include topographic and hydrographic maps based on the most recent surveys of the territory to be studied; detailed hydraulic data on slopes, stages, discharges, and floods; rainfall-and runoff-data; analyses of samples of material from the bed and banks of the stream; and general geological information. Full information is also required on existing and proposed levees, revetments, and regulating works, and on navigation-conditions and channel-dredging activities of the past. During the course of the experiment, representatives from the field maintain close contact with the laboratory, observe the results indicated by the model, and report on existing conditions in nature. Members of the laboratory staff also make visits to the locality represented by the model, in order to visualize the problem completely. By rigidly maintaining this intimate contact between laboratory and field it has been found possible to evolve results which are practicable, economically sound, and based on good engineering practice.

When all data required for the study have been assembled, the next step is a comprehensive analysis of the problem and a determination of the area to be included in the model. This selection of boundaries requires careful judgment, for economy dictates that the stretch of river and area of overbank included be kept to a minimum. Generally speaking, the critical area should be situated at or near the center of the model, and the upstream- and downstream-limits must be so fixed as to provide proper entrance- and exit-conditions. Next the extent of the overbank area is determined, its limits being selected to include, without constriction of flow, the maximum stages to which the model will be subjected.

After the model-limits have been sketched on small-scale maps, the scale-relations are selected. Here, again, judgment and practical experience are requisite. The first scales to be decided upon are those involving the fundamental linear dimensions, commonly called the horizontal and vertical scales, which are so intimately interrelated that each must be chosen with due regard for the other. In fixing the horizontal scale, consideration must be given, on the one hand, to the space available and to economy of construction, and, on the other, to the precision demanded in the ultimate solution. In selecting the vertical scale the prime consideration is that it be sufficiently large to permit of accurate measurement of water-surface levels and changes in the bed and banks of the model-stream. These two scales together determine the area-scale, and unless additional slope is provided in the model, fix the velocity-scale and discharge-scale as well. After they have been chosen, an analytical study is required, to make certain that turbulent-flow will be obtained and that the quantity of water required for operation will not exceed the available laboratory supply.

At this point the problem of effecting bed-action in the model similar to that in its prototype presents itself. Laboratory and field investigations have demonstrated that the configurations of the bed of a natural stream are almost entirely determined by the movement and deposition of particles too large or heavy to be carried in suspension, which are swept along the bottom. In addition to this it has been found that flowing water exerts on bed-material a tractive force proportional to the product of depth and slope, and that there exists for each type of bed-material a critical tractive force which must obtain to produce general movement of bed-load along the stream-bed. If this critical value can be determined for the material composing the bed of the natural stream, the depth at which movement begins in nature can be determined by dividing such value by the known slope of the natural watercourse. Then if the critical tractive force for the sand proposed for use in the model is similarly determined, the slope necessary to cause its movement at a corresponding model-depth can be obtained by a simple division. If sufficient slope is not provided by the geometric distortion resulting from the exaggeration of the vertical scale, an additional amount is obtained by a method known as tilting the model.

The critical tractive force for any given sand may be readily determined by the application of any one of several formulas or by the performance of actual flume-tests. While the experimental method is more accurate and reliable it is frequently difficult, if not impossible, to procure from a natural river a sample of sufficient size, and in such cases formulas based on the graphic curves of mechanical analyses must be resorted to. Where, on the other hand, large-volume samples are readily and cheaply procurable, the tilting flume is brought into use with a layer of the test-material distributed evenly over its bottom. Water is then passed through the flume at some constant depth but with slopes which are increased until general bed-movement occurs.

The product of the critical slope and the depth is then taken as the index of the critical tractive force, and this is subsequently checked by determining other combinations of depths and slopes necessary to produce movement.

Having made a preliminary determination of scale-values and model-dimensions, a detailed plan drawing is made showing boundaries of the model, locations of the templates, and all other essential features such as the weir-box, entrance-flume, tailgate, discharge-flume, and gages. This plan, together with the templates which have been previously plotted on paper, transferred to sheet steel and cut, are taken in charge by the construction group, which then proceeds with actual building. During the period of construction, inspection and advice are given by the engineer in charge of the group responsible for the design and subsequent operation of the model.

In case an outdoor location has been selected, the ground area is cleared, after which templates are set in place with care and precision. The spaces between them are filled with sand or well-tamped earth to within about two or three inches of their tops, and the final surface is then applied and molded to reproduce existing topography. The area representing the movable bed is left in the original templates as a continuous recess, into which the bed-material is placed. Brick and concrete are freely employed in the construction of entrance- and exit-flumes and retaining walls.

Before beginning experimentation all the working features of the model are thoroughly checked; the weir is calibrated, and the gages are set to required elevations. The sand-bed is then molded to shape and water is passed through the model for a period of several hours, during which a series of stages representative of average conditions in nature is simulated. This is called the verification-run, and upon its completion the configuration of the model-bed is compared with that indicated by field maps. In case the model is simulating natural conditions accurately, only those phenomena will be observed during the course of the run that are actually in effect in nature. This provides an excellent check on the ability of the model to reproduce natural conditions.

The final and most exacting check is the "flat-bed" test-run, at the beginning of which the sand of the movable bed is troweled to a horizontal plane. Successive high and low stages are then passed through the model, the run continuing until the action of the currents has shaped the bed to simulate that of the reach of river under investigation. These runs often require several hundred hours of continuous operation and are made for test-purposes only. Having once proved the model, all runs are commenced with the bed molded by aid of the male templates. Successive runs designed to test varying improvement-plans can thus follow in rapid succession.

After preliminary tests have established the reliability of the model in reproducing the characteristics of its prototype, actual experimentation may be commenced. Briefly, this consists of simulating in the model the proposed improvements, operating the model through cycles of flow, and recording the results. Having demonstrated the fidelity of the model in reproducing past and existing conditions, the experimenter can rely upon it to give accurate indications of the effects of various improvement-works proposed for future construction.

Let us now consider an actual problem, representative of those submitted to the United States Waterways Experiment Station, this particular one having arisen in connection with the development of plans for improvement of the Mississippi River in the vicinity of Brooks Point, Missouri.

The navigation-project on the upper Mississippi River provides for the maintenance of a navigable channel nine feet deep and 300 feet wide between Cairo, Illinois, and St. Louis, Missouri. The regulating program for securing this channel has included construction of permeable pile-dikes supplemented, where necessary, by low-water dredging. The crossing at Brooks Point, 25 miles above Cairo, continues to give trouble during each low-water season despite the fact that the flow is confined there by a system of eight pile-dikes. Surveys made during August and September of 1932 showed a straight, navigable channel, with average low-water depths of 14 feet, extending from the right bank at Mile 30 (above Cairo) to the center of the stream at Mile 24.5. Here the current swings again to the right bank, over a crossing with limiting depths of about five feet, to connect with another deep pool in the bend op-

posite Mile 23.9 Elimination of the annual dredging-operations at the crossing, it was thought, could only be effected by a realignment of the channel. To obtain this realignment it was proposed to remove several of the dikes on the left bank between Mile 28 and Mile 25, and to construct a system of not more than six dikes on the right bank between Mile 27.3 and Mile 26.0. It was believed that by this change the right-bank channel at Mile 27.5 would be deflected to the left bank, from which it would later swing more obliquely over the crossing at Brooks Point, thus shortening the crossing and producing navigable depths. As the plan involved a considerable expenditure of money it was submitted to the laboratory for model-study.

It was decided to include in the model the stretch of river between Miles 30 and 20 above Cairo. The area to be studied was thus located near the center of the model, with a sufficient reach of river reproduced above and below it to insure proper entrance- and exit-conditions.

The horizontal and vertical scale were respectively 1:1000 and 1:125. The sand for the movable portion was taken from the bed of the Mississippi near Vicksburg, and was found by laboratory tests to require no supplementary slope to insure proper movement. The complete scale-relations could now be calculated, and were as follows: Horizontal scale = $L_m/L_n = \ell = 1/1000$; vertical scale = $D_m/D_n = d = 1/125$; slope-scale = $S_m/S_n = s = 8/1$; area-scale = $\ell d = 1/125{,}000$; velocity-scale = $d^{2/3}s^{1/2} = v = 1/11.2$; and discharge-scale = $av = 1/1{,}400{,}000$.

It was next necessary to prepare the model operating-chart. A 10-year period of gage-records was the basis, and 16 hours was selected for the duration of one cycle. Using this chart in connection with a rating-curve for the same gage it was found that the highest stage to be simulated represented a flow of 1,350,000 cfs in nature, which, multiplied by the discharge-scale of the model, indicated that the maximum rate of flow required for the experiment would be 0.96 cfs.

A detailed plan and elevation of the model, showing all of its features, were then drawn and turned over to the model construction group. Construction required about 30 working days for a small group of men and the total cost was about $1100.

The usual routine of testing was pursued, commencing with a verification-run of 16 hours duration. The map of the results of this run showed excellent similarity to a similar map made from field surveys. A flat bed-run followed, which at the expiration of seven cycles, representing 112 hours of continuous operation, had produced bed-configurations quite similar to those in nature.

The experiment proper was begun by making a series of runs in which the existing dikes were removed as proposed and the first three dikes of the proposed system were installed. The results indicated that three dikes would be insufficient to produce the desired deepening and widening, but that the desired objective might be attained by the addition of the fourth or fifth dike in the system. These tests are still in progress, and will definitely indicate whether the proposed structures can be relied upon to make this reach of the River completely navigable. There is a strong probability that they will show the construction of one or two of the longest dikes to be unnecessary. Compared to the amount of money saved by eliminating these dikes, the cost of the model experiment is insignificant.

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INVESTIGATION OF WAVE-ACTION ON SEA-WALLS BY THE USE OF MODELS

Kenneth C. Reynolds

I--Introduction

Battering seas, high tides, and storm-driven, on-shore winds always cause heavy damage along the seacoast and particularly at many beach communities. The destruction of property is heavy, houses are isolated by the high water, and the need of adequate beach-protection is again vividly brought to the attention of the public.

Along the New Jersey shore where the sandy beaches are used as playgrounds by so many people, it is usually the policy to extend the beach oceanward by constructing jetties to hold the sand. This affords protection to the beach properties, since the wave-energy is dissipated on the sand before any serious damage occurs.

Along many exposed parts of the ocean-front some type of sea-wall is often used to break up the force of the wave before it reaches developed properties. Sea-walls are used on some parts of the Atlantic, Pacific, and Gulf coasts as well as at many places abroad.

A sea-wall at Winthrop, Massachusetts, is built of huge granite blocks and has a vertical fall. The high-tide still-water level comes within about five and one-half feet of the top of the wall. During a severe storm last winter the spray from the breaking waves often rose 40 to 50 feet in the air and was blown by the strong winds onto roadways and cottages. The force of such waves is tremendous. Frequently much sand, gravel, and even boulders are deposited by the water on shore-property.

II--Purpose of model-studies

The question naturally arises as to whether sea-wall design might not be improved. Models of sea-walls with miniature waves striking them offer the best way for studying the advantages and disadvantages of different types of walls. The ideal sea-wall would be one which did not permit any sand or water to pass over the top, was not excessively high, was not subjected to undermining or to destruction by wave-action, and was not too expensive to construct.

III--Description of apparatus

Model-tank--A concrete-walled basin, formerly used for a floating dry-dock model, in the River Hydraulic Laboratory of the Massachusetts Institute of Technology, was available for the research (Fig. 1). Inside it is 20 feet 2 inches long and 8 feet 0 inches wide at the near end and 6 feet 0 inch at the far end. A temporary longitudinal wooden bulkhead for part of the left wall provides a usable width of 6 feet 0 inch for the entire length.

Wave-machine--The waves are generated by a wave-machine driven by a 2-horse-power electric motor whose speed is stepped down by counter-shafts to a pair of cone-pulleys, one of which is on the drive-shaft (Fig. 2). An eccentric drive on each end of the drive-shaft provides different eccentricities and hence heights of waves and different depths of immersion, while guides keep the plunger rising and falling vertically. The front face of the plunger is adjustable.

Water-supply--During a test water is continuously supplied to the concrete basin, the water-level being kept constant by a skimming-weir six feet long.

Gages--A vertical point gage, located 8.9 feet from the plunger, gives the still-water level--a reading being taken when water is just overflowing the skimming-weir.

An aluminum float was used at first for indicating the height of the waves, but it failed to give the true values, particularly for the crest of the wave when it was observed that often the extreme crest would splash over the float. A piano wire, passing from the float-stem over pulleys to a weighted indicator, permitted readings to be made on a vertical staff-gage.

This gage was replaced temporarily by a sheet of galvanized tin, clamped to the concrete wall of the basin near the main gage. The tin was provided with projecting nails lying in an inclined plane which was normal to the sheet tin. The nails were spaced so that the vertical interval was 0.01 foot.

Sea-wall models--The waves pass along the basin to the far end (Fig. 1) where the various models of the sea-walls will be installed. The first tests are with a vertical wall parallel to the waves. The sandy beach in front is shaped by a templet, the ends of which are supported by the top of the wall and by the floor of the basin, the templet being moved normal to the sea-wall. The model sea-wall for the first tests is located about 16-1/2 feet from the plunger.

Fig. 1--Apparatus for studying wave-action on model sea-walls at River Hydraulic Laboratory, Massachusetts Institute of Technology (wave-machine in foreground, sea-wall in background)

As the waves pass over the beach and break against the wall, sand and water are often carried over it and are collected in a galvanized tin box of about 95.5 liters capacity. All sand is being measured volumetrically under water.

IV--Preliminary studies

Previous to the actual tests, a thorough study was made to ascertain if the waves as generated were correctly simulating nature.

It was soon apparent that the best speed of operation of the plunger was at the rate of 20.3 revolutions per minute. A higher speed created waves so close to one another that the waves as they broke on the beach were always interfering with the succeeding wave, so that no hammering effect occurred on the sea-wall. The slower speed permitted the water of one wave to recede before the next wave broke, so that the wall was subjected to the full blow of the wave. This permitted the greatest movement of sand and water over the wall.

At the adopted speed with certain slopes of the front face of the plunger, secondary and tertiary waves were formed which interfered with the primary wave. These were caused by the front face of the plunger moving the water forward on the down stroke, forming a wave. As the plunger started to rise, another wave of less height was created. It would have been possible to eliminate the secondary waves by speeding up the machine, but in view of the wave-action on the beach the slower speed was considered better. In nature, not every wave is damaging. When the receding water just meets the incoming wave at the breaking point, then the energy is much greater.

The angles for the face of the plunger which were studied varies from 66° forward

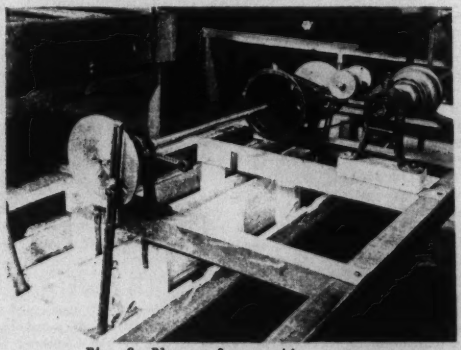

Fig. 2--Plunger for creating waves

Fig. 3

from the vertical to the vertical. The angle tentatively adopted was at 32° from the vertical. The criterion was the form of the wave and the absence of troublesome secondary waves.

With a model-scale of 1 to 48 and wave-heights from crest to trough of about 15 feet, the wave-length from one crest to the succeeding crest was observed as about 547 feet for nature. The wave-period or time of passage from crest to crest would correspond to 20.5 seconds so that the observed velocity of propagation was representing a speed of 26.7 feet per second.

These waves are to be classified as shallow-water waves since the wave-height is less than one-half the wave-length. Capt. D. D. Gaillard gives (Wave-action in relation to engineering structures, U. S. Government Printing Office, 1904, p. 44) the formula for the velocity of propagation of such waves in feet per second as

$$v = \sqrt{5.123\ b_s/a_s\ L}$$

in which b_s/a_s is the ratio between semi-minor to semi-major axis of the elliptical surface-orbits and for this case is 0.30 while L is the wave-length in feet. This gives the velocity as 29.0 feet per second, which compares favorably with the 26.7 feet per second observed.

Capt. Gaillard also discusses (pp. 110-114) the per cent of wave-height above still-water level, since the energy of this water may cause such extensive damage to so many maritime works. He cites some 34 observations on the Duluth Ship Canal in which the average elevation of wave-crest above still-water level is 64 per cent of the wave-height and not 50 per cent as might at first be assumed. In the model, this value is about 60 per cent.

There are two types of waves which occur in nature--those of oscillation and of translation--the latter being the type which causes sand-movement along a beach and damage to a sea-wall. Studies on the model indicate that near the plunger the wave is one of oscillation which continues as such until shallow-water changes it to a wave of translation.

V--Scope of the tests

The wave-action on various shapes of sea-walls will be investigated and, since a vertical wall is quite common, it will be used as the basis of comparison.

It is intended to study the effect of the height of the wall and the slope of the beach on the tendency for material to go over it and on the danger of undermining, methods of protecting the toe, methods for breaking up the energy of the wave, the most favorable distance of the wall from the breaking point. These studies will be made for waves approaching the sea-wall both normally and from various angles.

VI--Tests on a vertical sea-wall

For a typical vertical sea-wall, that at Winthrop Beach, Massachusetts, was selected where the maximum still-water level is about elevation 14.5 feet and the crest of the wall is at elevation 19.3. A model scale of 1 to 48 was adopted and waves about 15 feet high selected as typical storm-waves and all tests made for this still-water level and wave-height.

Parts of this beach have a slope of ten horizontal to one vertical and, for the initial tests, the sand was so sloped but with various heights of the beach varying from 19 feet to 4 feet (Fig. 3). The time required for the collecting box to fill with sand and water was observed, the experiment stopped, and the sand measured. This volume and time furnished a rate of movement of sand over the model which gave a fairly good curve. Tests were made for the top of wall at elevation 19.0 and at elevation 22.0.

For both walls there was no sand going over the wall when the beach was at elevation 4.0 although this region of the curves was not thoroughly investigated. The important part of the curves is that when the maximum rate was observed, the exposed wall was 7 feet high for the wall at elevation 19.0 and 8 feet high for the wall at elevation 22.0. Below these critical points, there was a tendency for undermining, while above, the sand gradually built up a sloping beach to the top of the wall. In other words, apparently there is a critical elevation of beach against a vertical wall so that if the beach is below this elevation there will be undermining to the detriment of the structure. With the lower beaches the wave breaks against the wall and the water is forced upward. When it drops, the water has receded enough so that the impact is on sand unprotected by a water-cushion and undermining results. When the beach is above the critical height, the wave breaks on the sand, runs up the beach carrying sand with it, thus building up the beach. Also considerable wave-energy is dissipated as the wave runs up the beach.

From these tests it appears that a change in the elevation of the top of the wall from 22.0 to 19.0 will cause nearly 50 per cent more sand to go over the top. This feature needs to be more fully investigated, since a considerable expense is involved in clearing up roadways and beach properties after a severe storm.

It is intended to study walls of other heights although, for the locality under consideration, lower walls are not feasible and too high walls would shut off the ocean-view of property owners.

The research has hardly been begun, but already it is apparent that these model-studies will greatly enrich our knowledge of sea-wall design.

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WAVE-MOTION IN A CHANNEL

John B. Drisko

There are numerous types of waves with which the hydraulic engineer must deal, such as tidal waves, flood-waves, waves in a canal due to the filling or emptying of a lock, power-waves, and so on. Power- or increment-waves will be the chief subject of this paper, and some mention will be made of experimental work on power-waves and tidal waves which has been done at the Massachusetts Institute of Technology.

Power-waves--A power- or increment-wave, formed by the sudden opening of a gate at the upper end of a channel, is somewhat akin to a solitary wave of translation, and a brief analysis of the latter will help to explain the former. In a rectangular channel containing still water, a solitary wave of translation, as shown in Figure 1, travels with a velocity $w = \sqrt{g(d+h)}$ (see Waves of translation by J. Scott Russell). The water in front of and behind the wave is motionless. The velocity of the water under the wave is much less than the wave-velocity, is uniform throughout any vertical plane perpendicular to the axis of the channel, and, for the particles in such a vertical plane, is given by the expression $v = [x/(d+x)]w$, where x is the height above the original surface-level of a particle on the surface of the wave and in the plane. The maximum water-velocity, under the crest of the wave, is $v_m = [h/(d+h)]w$. The length of a solitary wave, as given by J. Scott Russell, is from 6d to 6.28d. If the solitary wave is generated in flowing water having a velocity V, its velocity is simply $V + \sqrt{g(d+h)}$.

A power-wave superposed on still water, as in Figure 2, is generated when an increment of flow is admitted suddenly to the channel. The front of this wave, ideally,

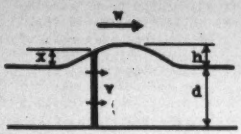

Fig.1

Fig.3

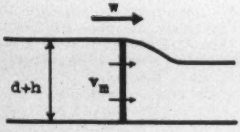

Fig.2

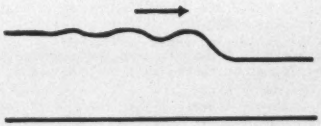

Fig.4

is the same shape as the front half of a solitary wave, and the increment of flow q = $v_m(d+h)b$ = whb, where b = channel-width. If the original water in the channel flows with a velocity V, then $q_1 = (V + w)hb$. The water-surface slope corresponding to this increased flow (after the wave-front has passed, the flow is hydraulic) will be greater than the original water-surface slope, and so as the wave-front travels downstream, the depth of water in the channel behind the wave-front must increase. As a result of this increase in depth due to increased slope-requirements, a large volume of water in excess of the amount furnished by q_1 must be supplied, actually, and is stored in the channel (Fig. 3).

The stage at any point along the stream will rise until such time as the depth has increased to a value at which the increased flow can be conveyed at the same slope as that of the original stream. In general, in a natural channel, the new condition of flow does not persist long enough for this to occur. Hence, stage-changes are greater at points upstream.

Inasmuch as the wave-length is approximately six times the depth, the wave-front of a power-wave is extremely short and passes a given point in a few seconds at the most. The large increase of stage occurring at the start of a power-wave and lasting for a much longer period, is due to the greatly increased slopes necessary for ordinary hydraulic flow immediately behind the wave-front.

As an example, let us assume a river 7 feet deep, flowing at an average velocity of 0.5 ft/sec. The wave-velocity at this depth is 15 ft/sec. A power-wave originally 0.2 feet high will accommodate a flow increase of $q_1 = 15.5 \times 0.2 = 3.1$ cfs per foot width, giving an increase of the stream-velocity from 0.5 ft/sec to $[(7 \times 0.5) + 3.1]/7.2 = 0.92$ ft/sec. Considering the Chezy formula $V = C\sqrt{RS}$ for the old and the new conditions, C and R change but little, and hence S must change very markedly.

If the flood-flow is maintained for a very long time, the depths will increase greatly and the slope will eventually drop back to the original value. Again, comparing the expression $Q = AC\sqrt{RS}$ for original and final conditions, S is to be the same, C will be slightly increased, and the bulk of the change in Q must result from increases in A and R, or really, of the depth.

Experimental work--The experimental work now in progress at the Massachusetts Institute of Technology is being carried on in a small channel 41.5 feet long, 15 inches deep, and having a mean width of 5 inches. The walls flare slightly. Water-levels at four points along the channel are continuously recorded full-scale on a moving strip of paper travelling one inch every four seconds.

Waves of translation--Observations of the velocity of solitary waves of translation checked the results of J. Scott Russell, which give the velocity as $V = \sqrt{g(d+h)}$. Here d is the original depth and h is the wave-height; in the case of a trapezoidal channel, d, or (d+h), is the cross-sectional area divided by the surface-width.

Tidal waves--Following the studies of solitary waves, tidal phenomena were investigated. A hinged waste-weir in the forebay at one end of the channel permits the generation of periodic tides. With the far end of the channel closed, the tidal wave travels along the channel, is reflected, returns, and is then negatively reflected from the open end of the channel. The superposition of the moving waves, travelling in two directions, produces an oscillatory condition, and the longitudinal surface-profile of the channel behaves much as a vibrating string; that is, nodes and loops, or points of zero tidal-range and regions of simultaneous high and low tide, are formed. The closed end of the channel becomes a point of maximum amplitude, or maximum tidal-range, and for a given depth the distance between nodes is a function of the frequency of the tides.

If the end of the channel away from the tidal disturbance is open, and connects with a large body of water, then that end of the channel becomes a node-point. Otherwise the phenomena are the same in both cases.

The distance between nodes is given by the expression $N = 1/2\ (P\sqrt{gd})$, in which P is the tidal period and $\sqrt{gd}$ equals the wave-velocity at the average depth. This relationship holds true only when the tidal range is small in comparison with the depth of water in the channel.

If the tidal range is large and the tidal period short, the wave becomes distorted and has a very steep front. The top of the progressing tidal wave travels faster and overtakes the underlying portions, for which the channel-friction is proportionately larger. In some cases the front of the wave becomes so steep that it breaks and continues as a bore. The oscillatory condition, somewhat modified, persists.

Power-waves--Power-waves are generated by suddenly introducing an increment of flow at the upper end of the channel. In cases where the extra flow is admitted slowly at first, numerous successive small wave-fronts are formed, and overtake each other until the ultimate wave-shape is reached, which corresponds to the front half of a solitary wave. The small initial wave travels at a velocity corresponding to the original depth of water. As soon as the ultimate wave-front is formed, the wave-velocity increases to correspond to the water-depth measured to the wave-crest. If the extra flow is admitted too abruptly, the wave-front is very steep and becomes flatter until it assumes the shape of the front half of a solitary wave. Apparently a perfect wave-front is a rare thing. The experimental results show the front of a power-wave to be somewhat as shown in Figure 4.

Much work remains to be done along the line of stage-changes at any point, and slope-changes immediately after the wave-passage.

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RUNOFF-INVESTIGATIONS FROM SMALL AGRICULTURAL AREAS

S. H. McCrory

The Bureau of Agricultural Engineering has, since 1910, been studying the problem of runoff from small areas of land. Early studies would be considered crude today but the technique has been gradually improved until now we feel that the studies cover fairly adequately the purposes for which they are made.

The first studies undertaken were made for the purpose of determining the amount of runoff that should be provided for drainage-ditches that were to provide artificial drainage for cultivated land. When I joined the staff of Drainage Investigations, Office of Experiment Stations, in 1907, one of the most points in the design of drainage-

Table 1--Relation of rainfall to surface-runoff for certain storm-periods

Storm-period	Bogue Phalia near Head, drainage-area 463 square miles			Bogue Phalia West of Shaw, drainage-area 216 square miles			Horseshoe Bayou East of Cleveland, drainage-area 27 square miles			West Bogue Hasty at Litton, drainage-area 317 square miles		
	Rainfall	Runoff		Rainfall	Runoff		Rainfall	Runoff		Rainfall	Runoff	
1924	ins	ins	o/o	ins	ins	o/o	ins	ins	o/o	ins	ins	o/o
Feb.23-26	3.25	1.83	56	3.28	1.96	60	....	....	..	3.32	2.12	64
Apr. 9-17	3.02	1.00	33	3.26	0.92	28	....	....	..	3.08	1.04	34
May 26-June 1	4.12	1.08	26	4.25	1.20	28	4.18	0.95	23	4.35	1.80	41
1925												
Mar.13-18	3.35	0.95	28	2.95	0.87	29	3.56	1.02	29	3.72	1.55	42
Nov. 3-19	9.66	4.94	51	9.10	....	..	12.78	7.42	58	11.50	....	..
Dec.13,14	3.02	1.27	42	2.92	1.26	43	2.96	1.57	53	2.98	1.95[a]	65
1926												
Jan.20,21	1.87	0.81	43	1.76	0.68	39	2.20	0.95	43	1.83	1.12[a]	61
Mar. 6,10,11	3.58	1.46	41	3.49	1.40	40	3.65	1.31	36	3.46	1.56	45

[a]Results probably high.

ditches was the amount of runoff it was necessary to provide for in order to secure adequate drainage. About the only data available were the records of the United States Geological Survey in regard to the discharge of streams and every engineer engaged in this work--and there were not so many of us in those days--had his opinion as to the proper amount of runoff to provide for, but very little information with which to back his judgment. Consequently, the arguments were numerous and at times heated.

As drainage-work developed in different parts of the country the need for definite information became more and more apparent; C. G. Elliott, then Chief of Drainage Investigations, in 1911 authorized the first investigations which were undertaken in southeastern Missouri and in western Tennessee. Later, after some of the large districts in the South were completed and large areas of land brought under cultivation, it became apparent that it was going to be necessary to clean out and enlarge the ditches if adequate drainage was to be secured. There was an insistent demand for this information and in the fall of 1914 C. E. Ramser was sent to Bolivar County, Mississippi, to make a study of the runoff from the Boque-Phalia Drainage District which the land-owners in that District expected to reconstruct within a year or two in order to secure more adequate drainage. A number of gaging-stations was selected and provisions made for determining the discharge from the different watersheds and slope-measurement courses for determining the value of "n" in the Kutter formula. During the period these investigations were carried on, information was secured which was of great value in determining the proper coefficient of roughness in designing drainage-ditches and in determining the amount of runoff that must be provided for in areas similar to the district in Bolivar County. After the ditches had been redug, additional measurements were made during the period from December 1923 to June 1926 and observations on flood-stages were continued until the Mississippi River levee broke in April 1927. The relation of surface-runoff to rainfall for certain storm-periods is shown in Table 1. The work was then extended to other areas in different parts of the United States and investigations were made on the hill streams in the vicinity of Tupelo, Mississippi, where drainage-improvements had been installed, on the flat lands in Robeson County, North Carolina, on the Missouri bottoms and tributary streams in western Iowa near the Missouri Valley, on ditches and large tile in southwestern Minnesota, on the prarie in the vicinity of Urbana, Illinois, on drainage-ditches near Fort Wayne, Indiana, on ditches and floodway near Cape Girardeau, Missouri, and are now in progress on ditches in the vicinity of Bowling Green, Ohio, and Dover, Delaware.

When the Division of Drainage Investigations was transferred to the Bureau of Public Roads, the study was broadened to include small areas such as would commonly be served by culverts or small ditches where they crossed highways.

Reports on these investigations have been issued in mimeographed form. Unfortunately, our supply of these publications is largely exhausted. It is hoped ultimately to bring together in one publication the results of these investigations. The material on the coefficient of roughness in drainage-channels has, however, been brought together by C. E. Ramser (Flow of water in drainage-channels, U. S. Dep. Agri. Tech. Bull. 129-T). A report on the enlargement of drainage-ditches, based on information obtained largely from these studies, has also been prepared by Mr. Ramser (Erosion and silting of dredged drainage-ditches, U. S. Dep. Agri. Tech. Bull. 184-T).

Several years ago the interest in soil-erosion became great and Congress appropriated money for an investigation looking to its prevention and control. The Department, in cooperation with State agricultural experiment stations and other State and local agencies, has established ten soil-erosion stations on ten highly erosive soil-types in the United States. These stations are operated cooperatively by the Bureau of Chemistry and Soils and the Bureau of Agricultural Engineering. In the order of their establishment, they are: Guthrie, Oklahoma; Temple, Texas; Hays, Kansas; Tyler, Texas; Bethany, Missouri; Statesville, North Carolina; Pullman, Washington; Clarinda, Iowa; LaCrosse, Wisconsin; and Zanesville, Ohio.

The control of soil-erosion is, in the last analysis, largely a matter of the control of surface-runoff, and studies of the runoff from areas on these stations form an important part of the work. At these stations for the first time we have had funds to properly equip the work and to maintain a fairly adequate staff.

At each of these stations we have installed a series of experiments on cultivated terraced and unterraced lands with different negative cover and are measuring the runoff from these areas. We are also determining, as accurately as possible, the amount of soil eroded from each area. Where the size of the area is not too large, the discharge is measured with a Parshall measuring-flume of proper size and on as many of these areas as are possible, we have installed a silt-sampling device with which we measure the amount of silt removed from the areas. In addition to the terraced areas, other areas with different types of cover are selected from which the runoff is determined. For instance, on all of the farms where practicable, we are measuring the runoff from areas of terraced and unterraced cultivated land, pasture-land, and forested land. Off the station we are selecting areas of somewhat larger size with different cultural conditions where complete record of the runoff is kept. The Bureau of Chemistry and Soils is also measuring the discharge from a series of small plots with different covers. Each station is provided with two or more automatic rain-gages and a number of standard Weather Bureau gages which are so located over the farm that the variation in intensity of any given storm may be determined. So far, no reports have been published on these investigations but a progress-report on the Guthrie station is about ready to go to the printer.

These studies as they progress will undoubtedly give much valuable information in regard to the effect of tilth of the soil, effect of different types of cover and cultural practices upon runoff from agricultural lands. Studies so far indicate that the greater part of runoff occurs, as would be expected, during the periods of heaviest rainfall. Quick, intense precipitation seems to be more effective in causing erosion. The effect of different cultural practices on runoff from agricultural lands is interesting. For instance, at Hays, Kansas, in 1932 it is reported that the runoff from listed land was 3.19 inches, from land plowed with a one-way plow 5.12 inches, from lands stubbling in, burning, and one-way plowing, 5.2 inches, and moleboard-plowing 4.07 inches.

At Pullman, Washington, in 1932, a greater amount of runoff occurred from the gentle slopes than from the steeper slopes due to the fact that a large part of the year's runoff came from the year's snow which accumulated to a greater depth on the gentler slopes than on the steeper slopes. In 1932 the runoff in inches from two comparable terraced areas on land having slopes of 14.5 and 23.5 per cent was 4.23 and 1.64 inches, respectively. A comparison of terraced and unterraced areas on the Guthrie Project during 1932 showed that the unterraced areas lost 30.8 per cent of the total rainfall as runoff while terraced land similarly sloped and cropped in an identical manner lost 23.3 of the year's rainfall as runoff.

Recently there has been some discussion in regard to the advisability of attempting to determine the extent to which it was desirable to hold precipitation on

land on which it fell. Studies bearing on this point have been made at a number of the erosion-stations. At the Texas State erosion-station at Spur, Texas, it has been found practicable to greatly increase the yield of cotton by constructing terraces to hold all the precipitation upon the land on which it falls. The annual precipitation at Spur is approximately 20 inches per year. Similar studies at Guthrie, Oklahoma; Temple, Texas, and Tyler, Texas, have shown that in regions with 30 inches or more of rainfall, it is unsound agricultural practice to attempt to hold all of the water on the land.

At Temple, Texas, in 1932 with 34.19 inches of rain the runoff from areas planted to row crops range 3.1 to 5.8 per cent of the annual, planted to grains from none to 0.09 of one per cent.

Bureau of Agricultural Engineering,
U. S. Department of Agriculture,
Washington, D. C.

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